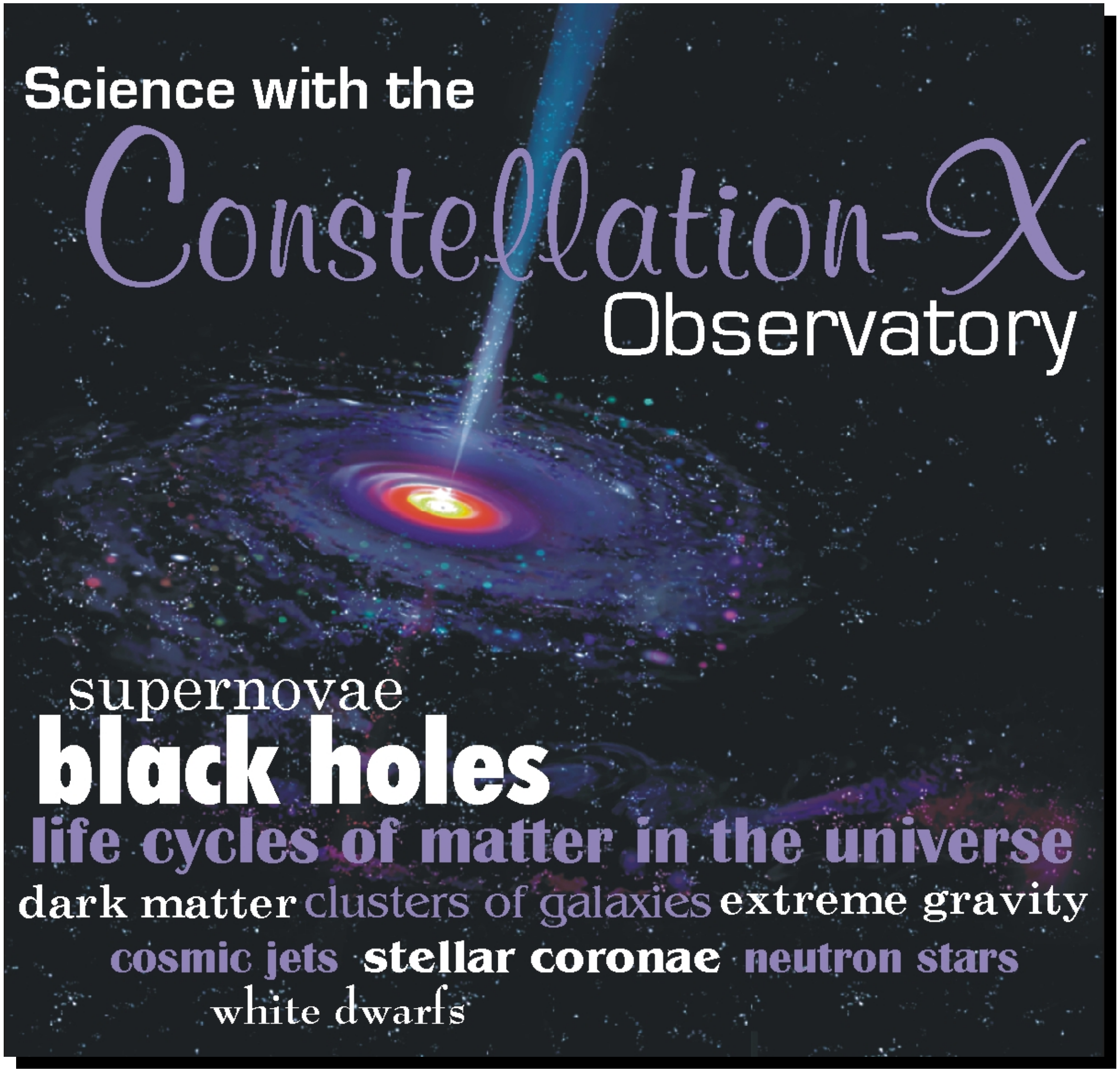
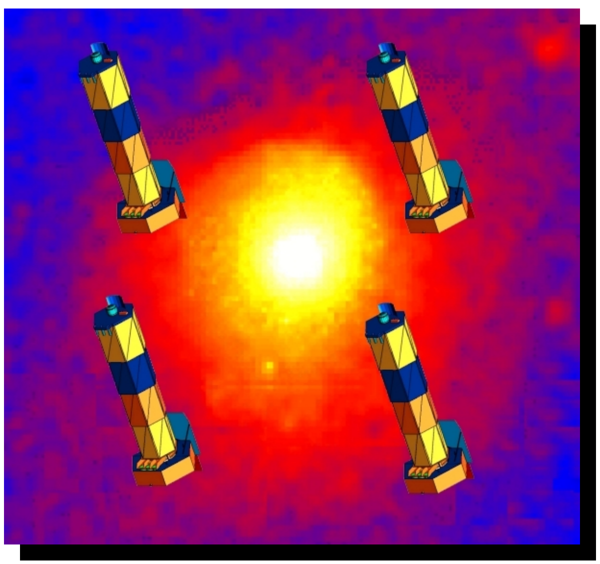
The Constellation X-ray Mission



Executive Summary

High throughput, high resolution, broad band spectroscopy

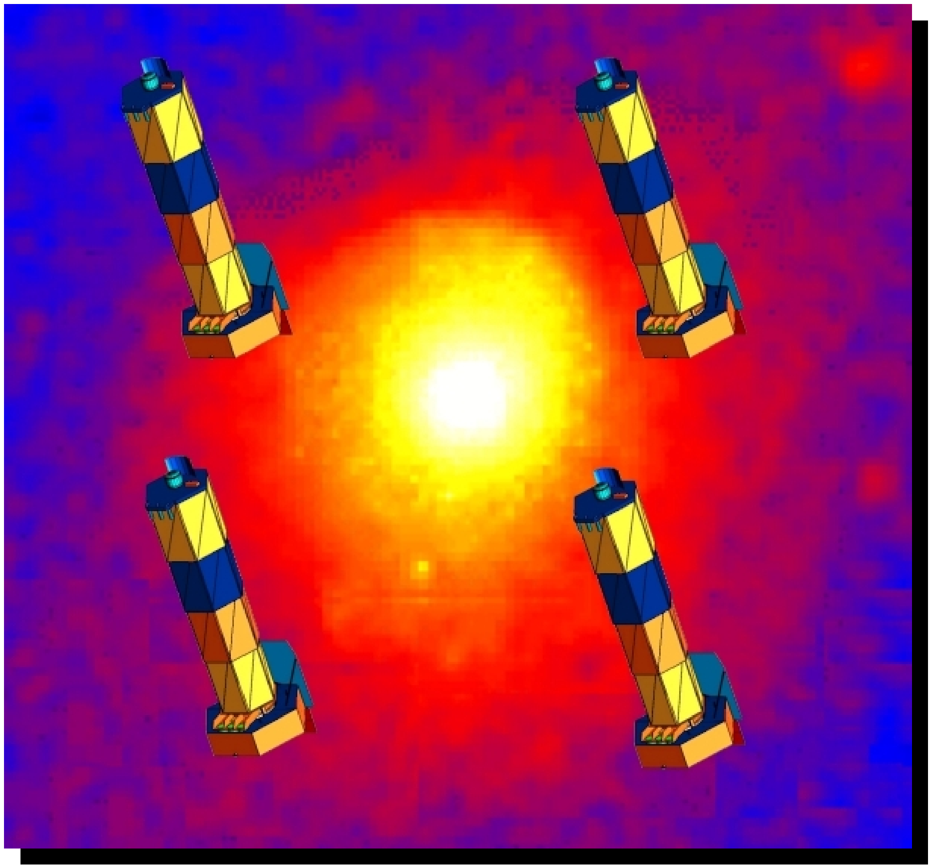


An X-ray Keck Observatory

- Constellation-X is a key element in NASA's Structure and Evolution of the Universe (SEU) theme
- Constellation-X will address many pressing questions concerning the extremes of gravity and the evolution of the Universe, e.g.,
    - Use broadened iron emission lines in Active Galactic Nuclei to measure black hole masses and spins and investigate General Relativity in the strong gravity limit
    - Show how black holes evolve with cosmic time and provide critical information on the total energy output of the Universe
    - Look across a broad range of redshift to reveal the earliest formation of clusters of galaxies and tell us whether their properties are consistent with current models of galaxy formation
    - Search for a hot, metal-enriched Intergalactic Medium as the resolution to the “missing baryon” problem

The Constellation X-ray Mission

Studying the life cycles of matter in the Universe . . .



Constellation-X

- Key scientific goals
  - Elemental abundances and enrichment processes throughout the Universe
  - Parameters of supermassive black holes
- Methodology
  - Plasma Diagnostics via high resolution spectroscopy
  - Continuum determination using a broad band pass
- Mission parameters
  - Effective area: 15,000 cm^2 at 1 keV
    100 times AXAF and XMM for high resolution spectroscopy
  - Spectral resolving power: 3,000 at 6.4 keV
    5 times Astro-E calorimeter
  - Band pass: 0.25 to 40 keV
    100 times increased sensitivity at 40 keV

The Constellation X-ray Mission History

Two peer-reviewed mission concepts selected by NASA in March 1995 for possible flight during the next decade were merged into the High Throughput X-ray Spectroscopy (HTXS) Mission in late 1995:

- ***The Next Generation X-ray Observatory*** - PI: Nicholas E. White (NASA/GSFC)
- ***Large Area X-ray Spectroscopy Mission*** - PI: Harvey D. Tananbaum (SAO)

Includes elements of a third accepted mission concept:

- ***Hard X-ray Telescope*** - PI: Paul Gorenstein

Addresses several primary and secondary NASA space science priorities (the TGSAA report) including

- Measurement of the properties of black holes of all sizes
- Study of the origin and evolution of the elements

Selected in May 1997 as a new mission to be proposed for a FY2004 new start at the Space Science Enterprise Planning *Breckenridge* Workshop.

In Summer 1997, entered pre-Phase A study as facility class mission

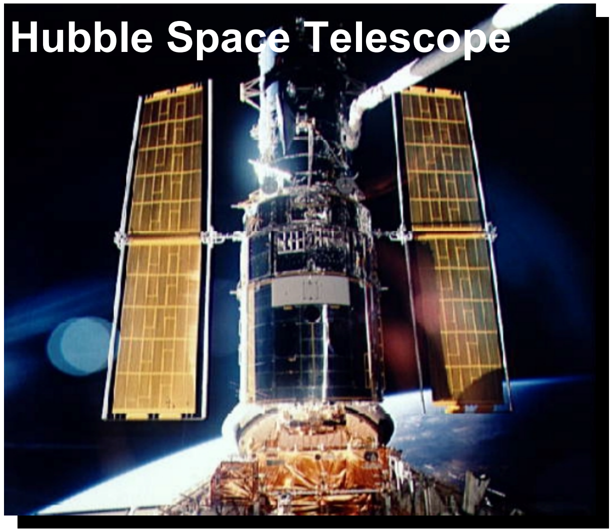
- GSFC/SAO project team established
- Facility Science Team (FST) created to provide oversight
- Renamed The Constellation X-ray Mission (Constellation-X) in October 1997
- Seven proposals in response to NRA 98-217-01 selected via peer review in April 1998 to participate in C-X technology development
- TRW and BATC selected competitively in May 1998 for mission architecture CAN studies

Current Status

- Currently in Mission formulation phase
  - Mission reference 4 s/c dual launch design now established
  - Industry (TRW & Ball) designs and reports delivered in Sept 1999
- Technology program underway with rapid progress in optics and detectors
- New start will not occur until the technology is ready
  - Project's target is for new start (C/D) in 2005, with 1st launch in 2008
  - Current funding will give new start in 2007, with 1st launch in 2010

X-ray Equivalent of the Keck Telescope

Imaging

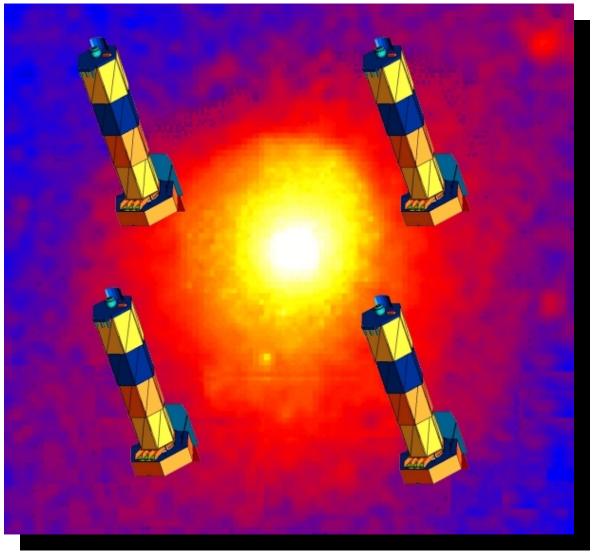


0.1 arc sec
40,000 cm^2

0.6 arc sec
1,000 cm^2
(100 cm^2)*

Spectroscopy

≤1 arc sec
780,000 cm^2

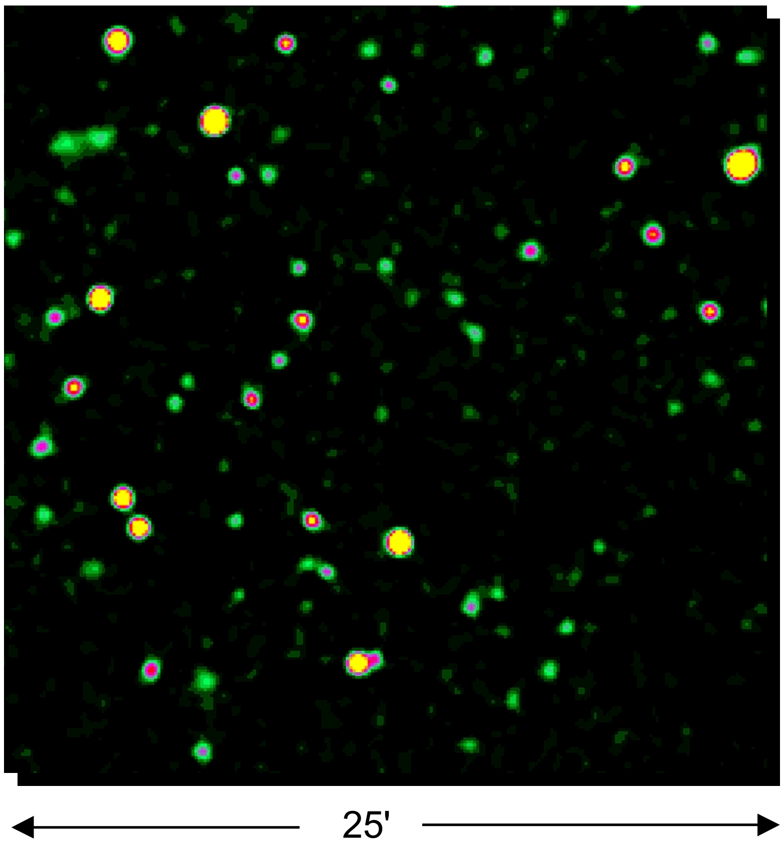


≤15 arc sec
30,000 cm^2
(15,000 cm^2)*

* effective area at the spectrometer

ROSAT Deep Field

Thirty-five years after discovery of the Cosmic X-ray Background, ROSAT has resolved into discrete sources ~80% of the background at 1 keV



- One million second ROSAT High Resolution Imager exposure of the Lockman hole region
  - Ten times fainter than Einstein deep field
  - Deepest X-ray image of the sky so far
- Optical identification programs reveal that many are AGN at a mean redshift of 1.5
  - reaching out to redshifts as high as 4
  - no evidence for a decline in the X-ray selected QSO population towards higher z
- ASCA and BeppoSAX deep fields show evidence for absorbed population of AGN
- Predict up to one million AGN will be discovered by AXAF and XMM

Constellation-X will be able to take detailed high resolution spectra for all of the sources pictured here.

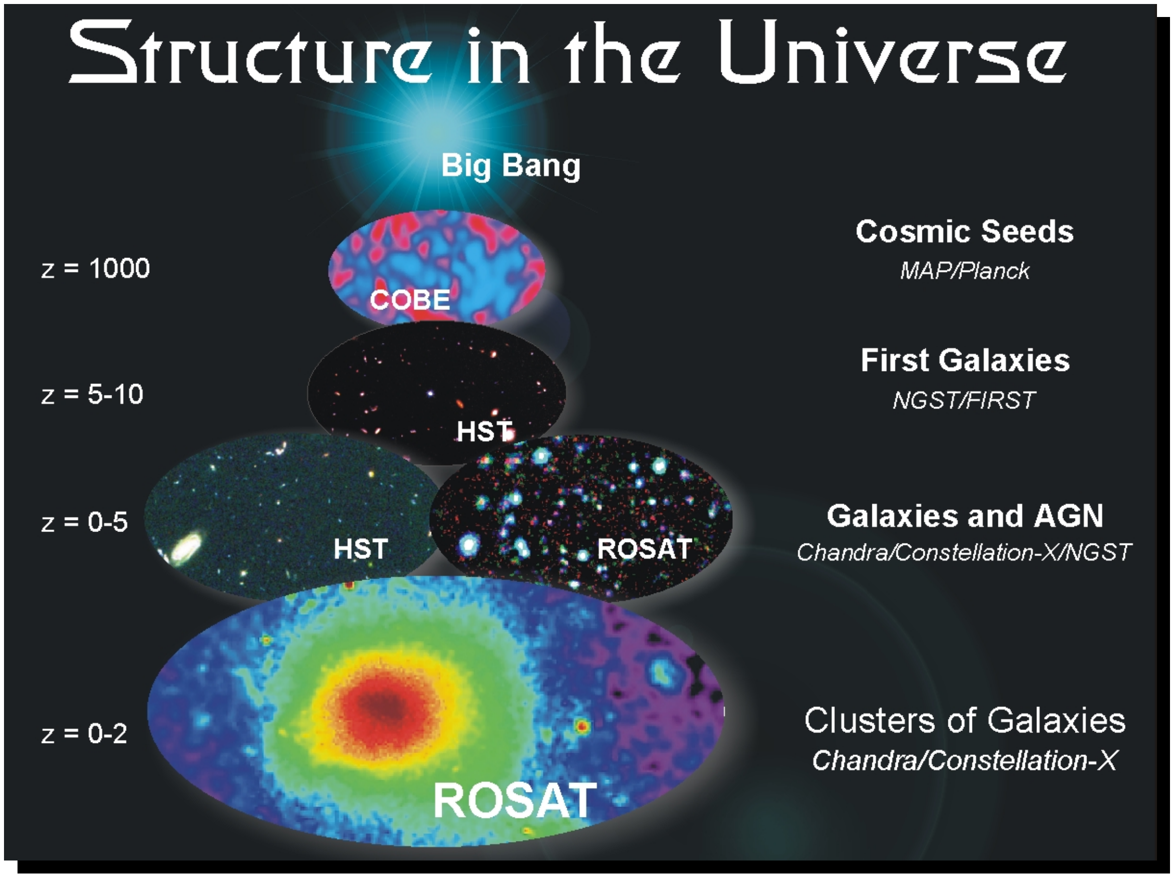
Structure in the Universe

Models of the Universe aim to account for all structure from

- fluctuations in the Cosmic Microwave Background (CMB)
  - the formation of the first galaxies

to the largest structures in the Universe

- clusters of galaxies



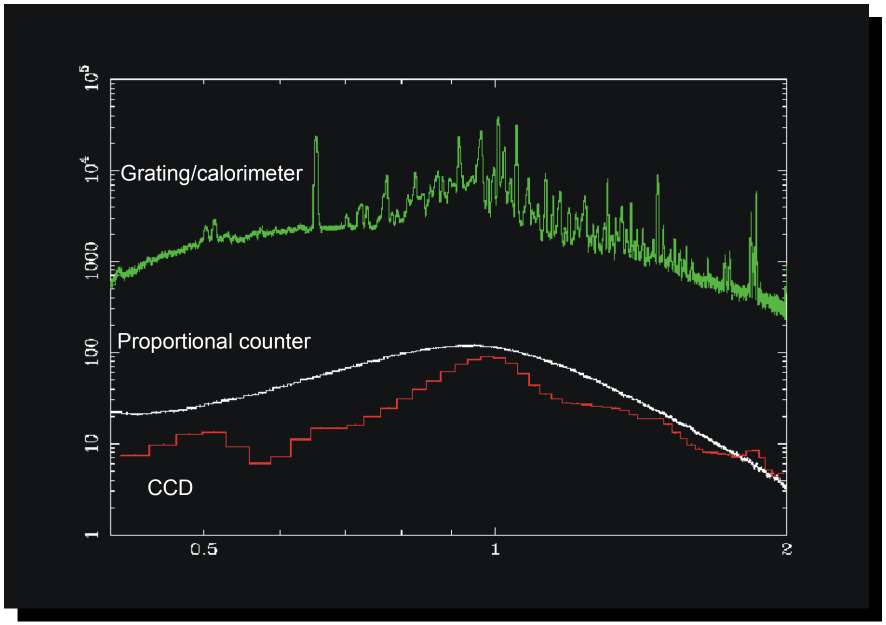
MAP and Planck will study the Cosmic Microwave Background

NGST and FIRST will zoom in on the birth of the first galaxies

NGST, Chandra (AXAF), and Constellation-X will observe the evolution of AGN and starburst galaxies

Chandra (AXAF) and Constellation-X will address fundamental questions related to the formation epoch and evolution of clusters of galaxies

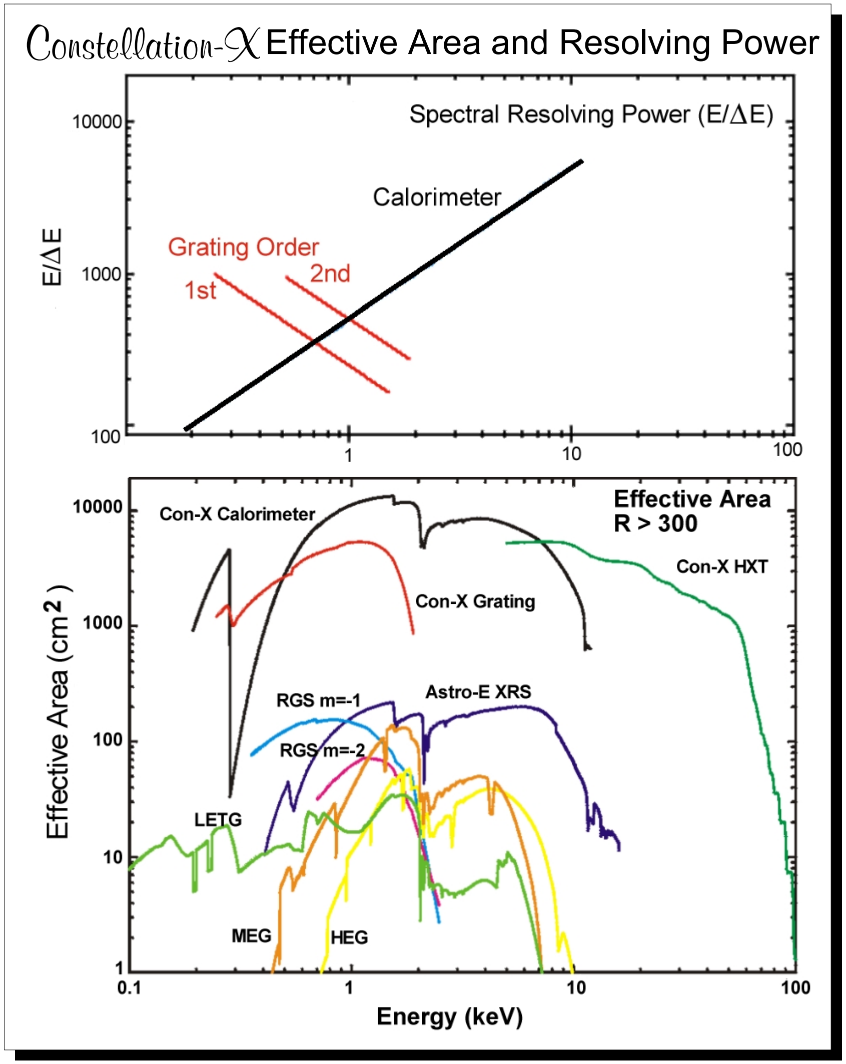
X-ray Astronomy Comes of Age



- The 0.25 to 10 keV X-ray band contains the K shell lines for all of the abundant metals (carbon through zinc) and the L shell lines of most.
- X-ray line spectra are rich in plasma diagnostics
  - density
  - temperature
  - ionization state
- Energy resolution of CCDs not sufficient to exploit these diagnostics
  - gratings and mircocalorimeters can provide required resolution (E/ΔE) ≥300
  - factor of 100 increase in collecting area over AXAF, XMM, and Astro-E required to reach faint populations
  - broad band pass (0.25 to 40 keV) required to determine continuum and search for absorbed sources

Constellation-X Mission Parameters

Two coaligned telescope systems cover the 0.25-40 keV band.



A 0.25 to 10.0 keV spectroscopy X-ray telescope (SXT)

- microcalorimeter array with 2 eV resolution.
- a reflection grating/CCD to maintain resolution > 300 below 1 keV
- ≤ 15 arc sec angular resolution

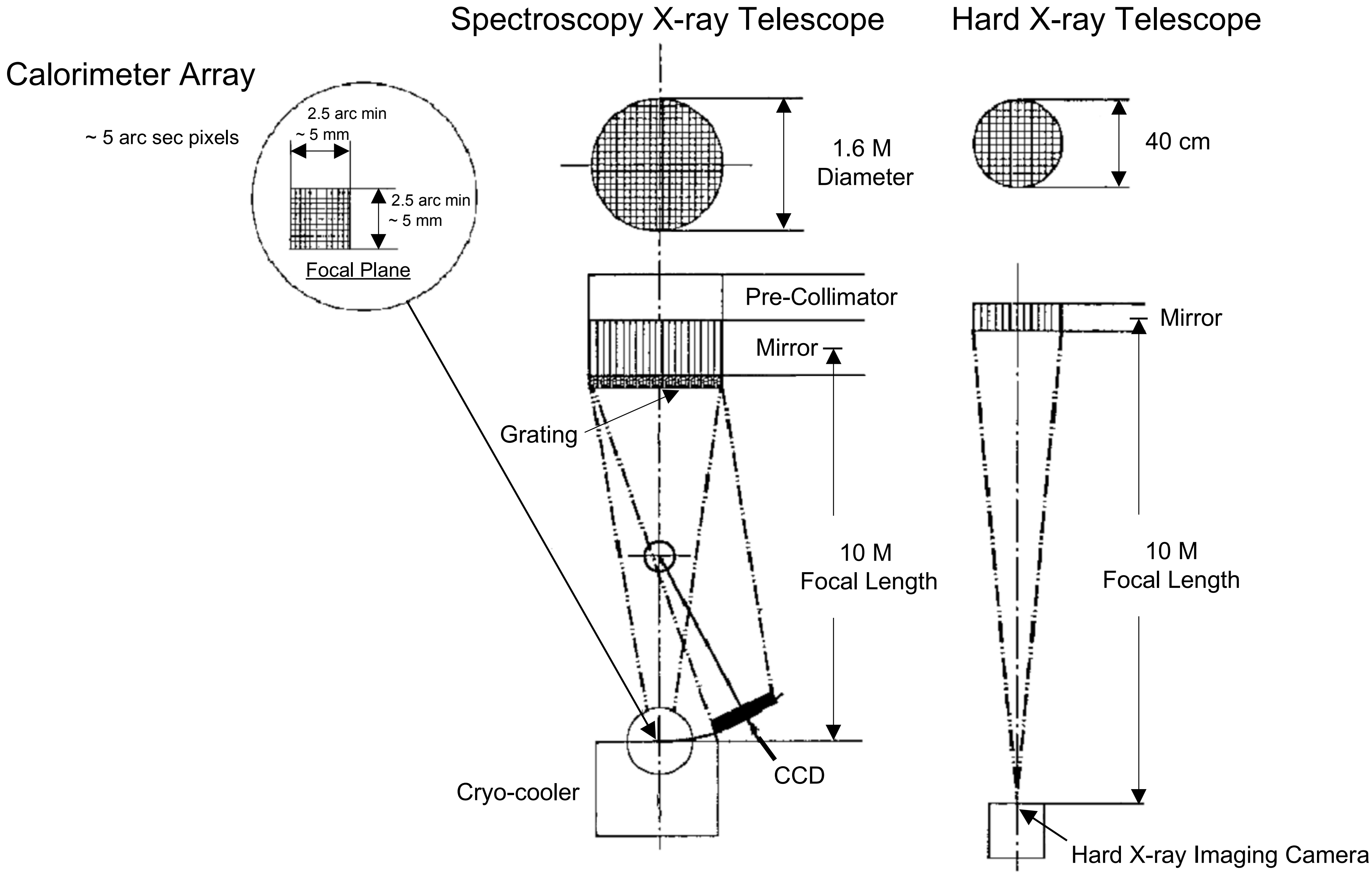
A 10 to 40 keV hard X-ray telescope (HXT)

- grazing incidence optics
- an energy resolution ~1 keV, sufficient to measure the continuum
- ≤ 1 arc min angular resolution

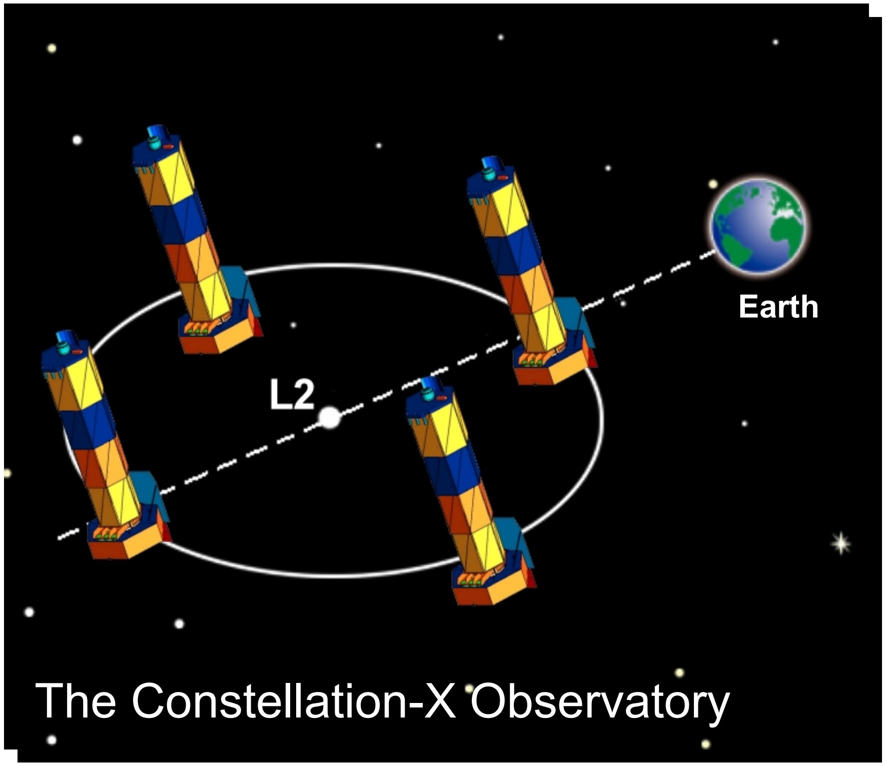
Factor of 20-100 increased sensitivity

- gives ~ 1000 counts in 10^5 s for a flux of 2 X 10^{-15} ergs cm^{-2} s^{-1}(0.1–2.0 keV)
- SXT angular resolution matched to confusion limit
- Increase in sensitivity equivalent to going from 2 m to 8 m for ground-based telescopes.

Constellation-X Instrumentation



A Multi-Satellite Constellation-X Approach to Large Collecting Area



To achieve 15,000 cm^2 effective area on a single satellite requires a Titan-class launch.

An alternative low-risk approach to achieve large X-ray collecting area is to utilize a constellation of identical Delta-class satellites.

Launched over 18 months.

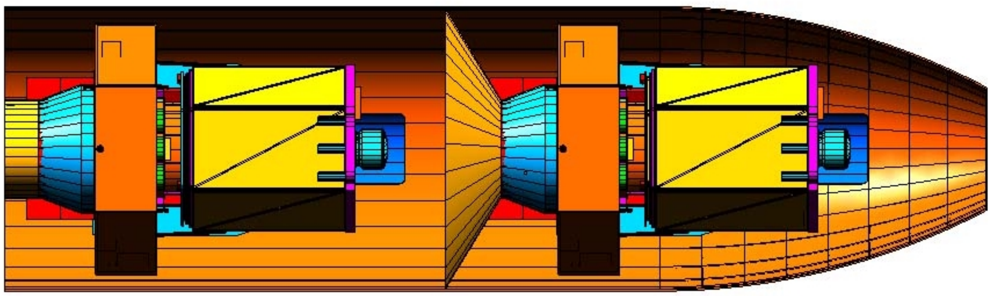
Facilitate simultaneous viewing and high efficiency by using libration point orbit.

The telescopes require a focal length of 8-10 m and use an extendible optical bench to allow a Delta-class launch.

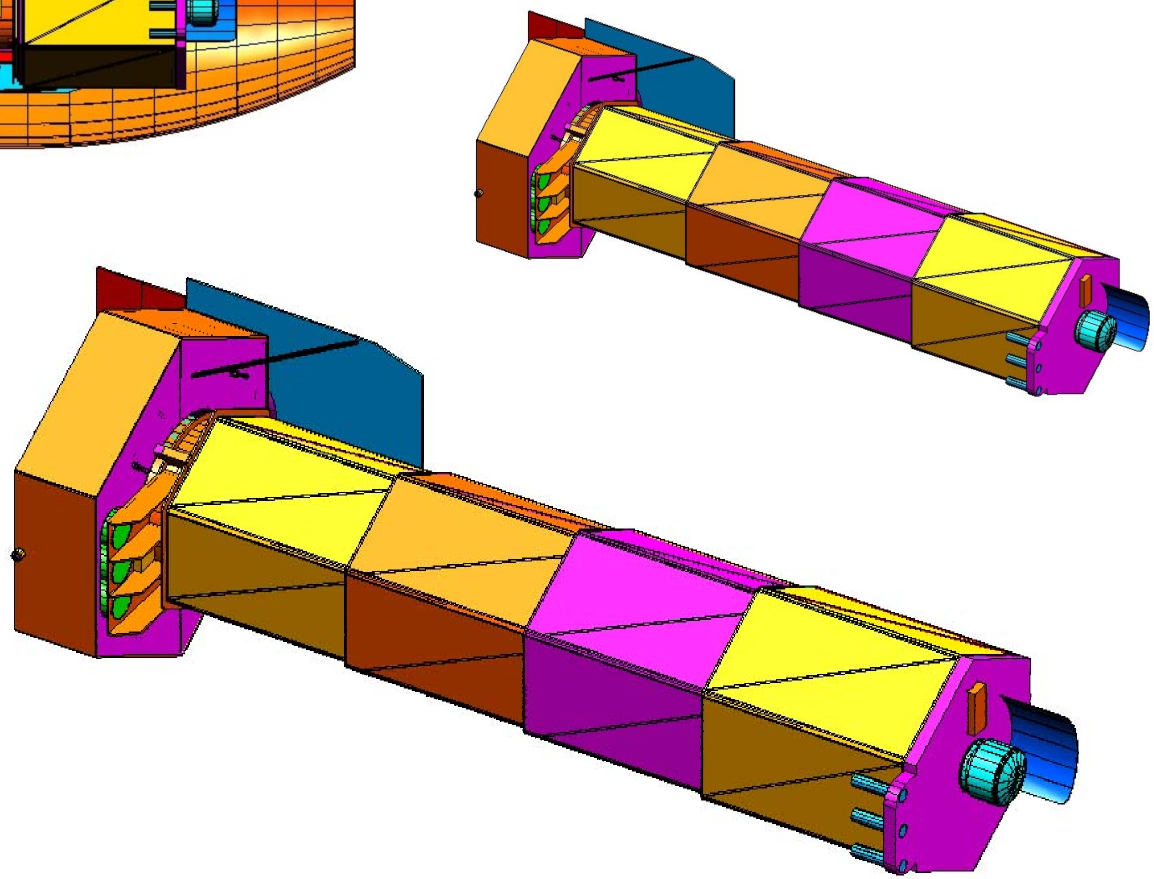
Each spacecraft design lifetime is three years, with consumables targeted for a five-year or longer mission.

Spacecraft Configuration

Delta IV or Atlas V class launch vehicle

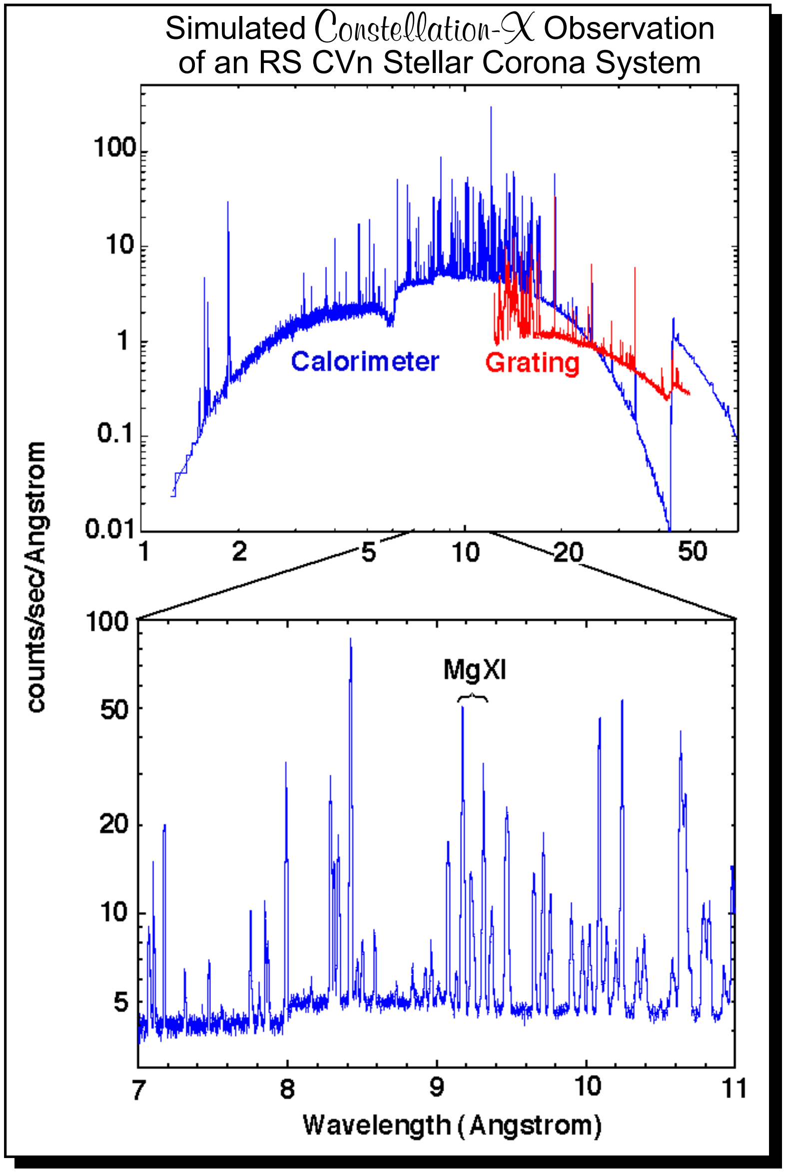


Stowed
(two spacecraft)



Deployed

Abundance Determinations with the Constellation X-ray Mission



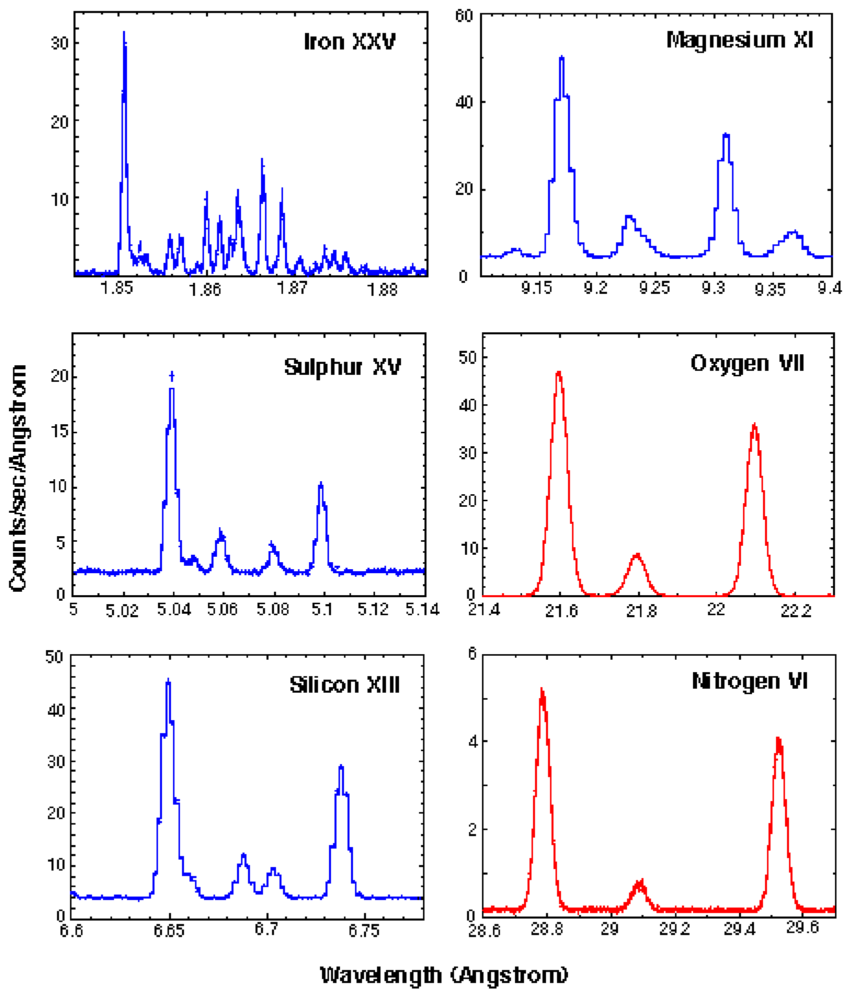
The Constellation-X energy band contains the K-line transitions of 25 elements allowing simultaneous direct abundance determinations using line-to-continuum ratios

The sensitivity of Constellation-X will allow abundance measurements in:

- intergalactic medium
- intracluster medium
- halos of elliptical galaxies
- starburst galaxies
- supernova remnants
- the interstellar medium
- stellar coronae
- young and pre-main sequence stars
- X-ray irradiated accretion flows

Temperature, Density, and Velocity Diagnostics

A Selection of He-like Transitions Observed by Constellation-X



The spectral resolution of Constellation-X is tuned to study the He-like density sensitive transitions of Carbon through Zinc

Direct determination of

- densities from 10^8 to 10^{14} cm^{-3}
- temperature from 1-100 million degrees.

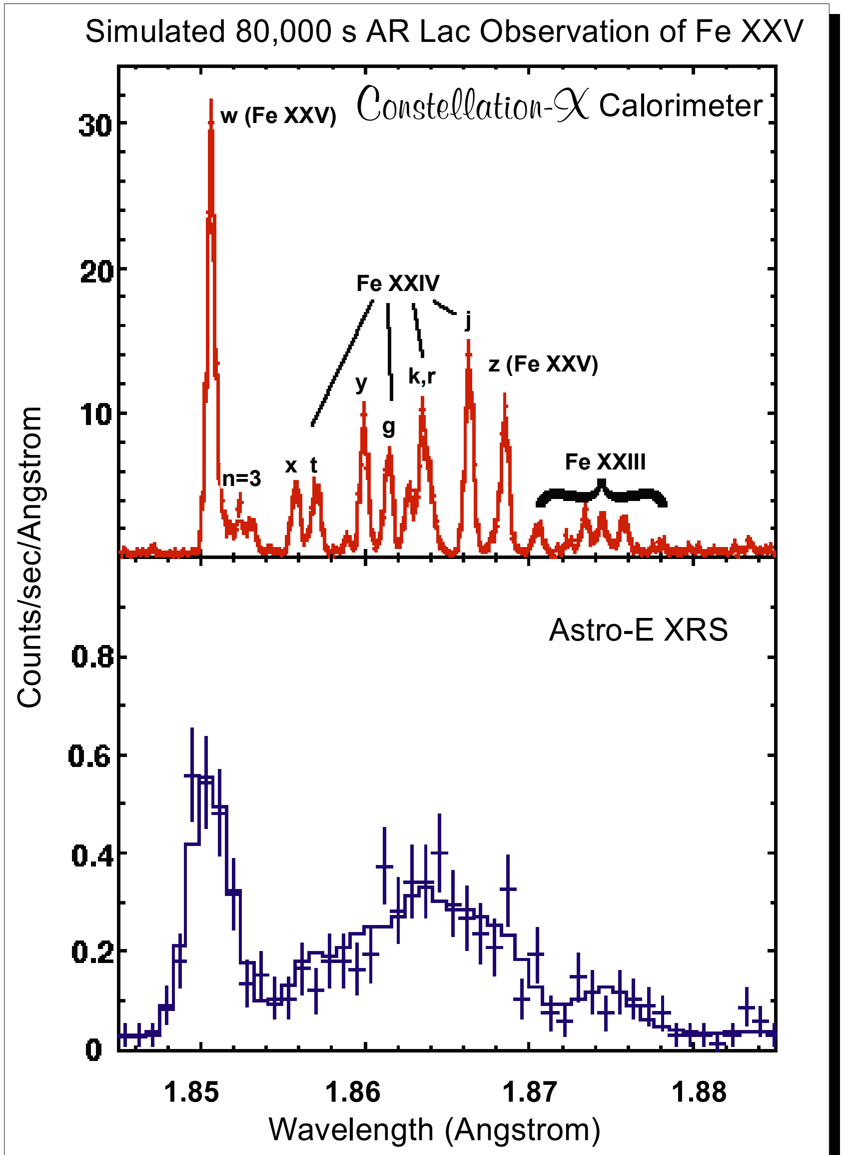
Velocity diagnostics at Fe K line:

- line width gives a bulk velocity of 100 km/s
- line energy gives an absolute velocity determination to 10 km/s

Simultaneous determination of the continuum parameters

- crucial for abundance determinations
- identify non-thermal components

Constellation-X Advanced Capabilities
High Spectral Resolution



The Next Generation Microcalorimeter Array

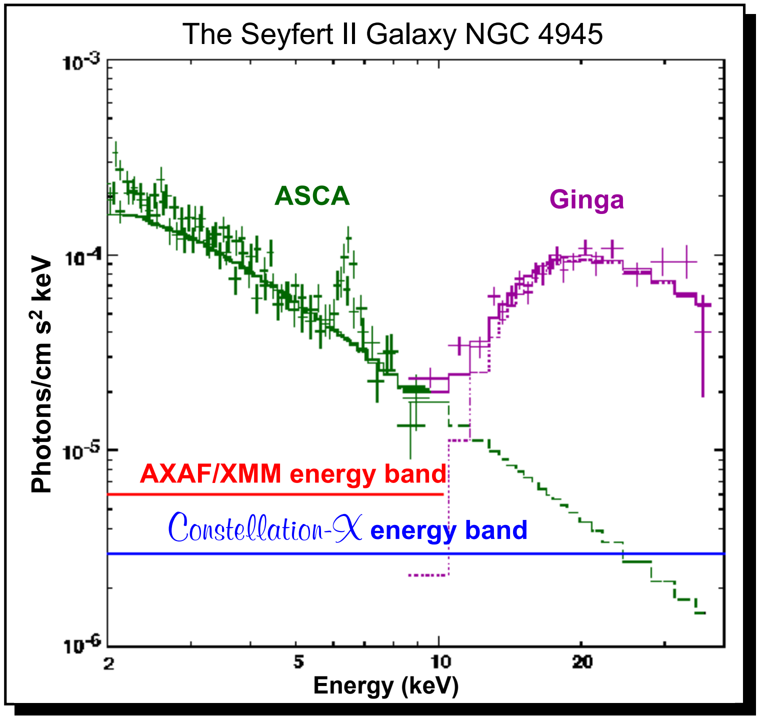
High quantum efficiency with the capability to map extended sources

- A factor of 5 improvement (to 2 eV) in spectral resolution
- Successor to the calorimeter to be flown on Astro-E (2000-2002)
- At Iron K, 2 eV resolution gives a velocity diagnostic of 10 km/s
- $\geq 2.5 \times 2.5$ arc min field of view

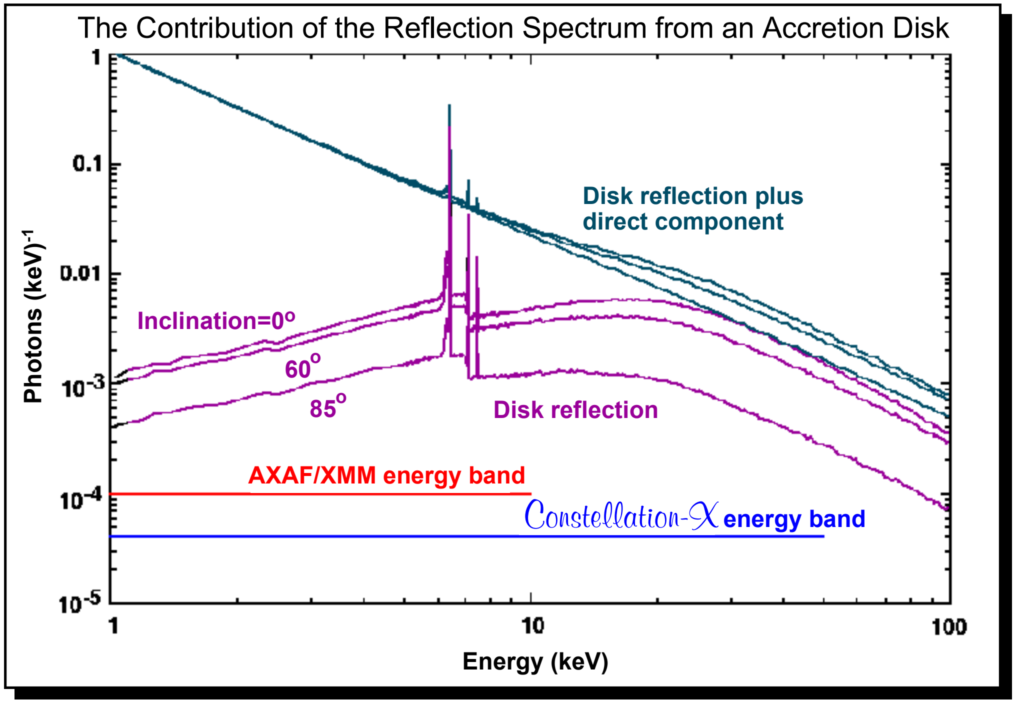
Hard X-ray Capability

The hard X-ray band is crucial to determine the underlying continuum

Planned missions (AXAF, AMM, Spectrum XG, and Astro-E) have limited or no sensitivity above 10 keV



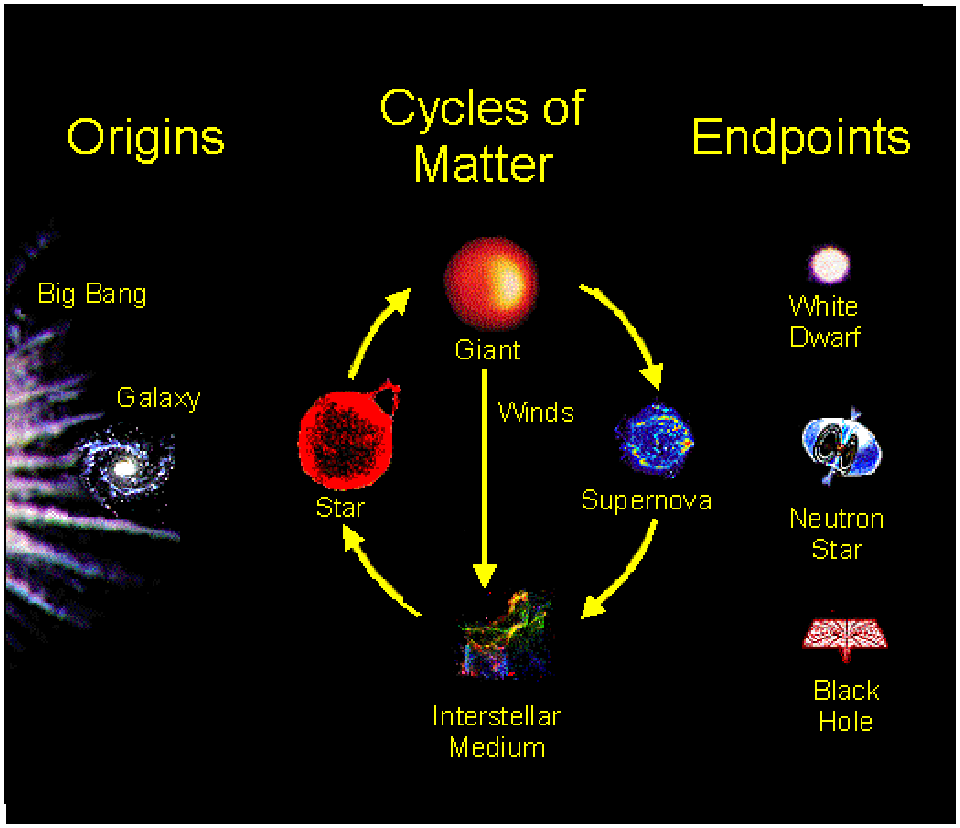
AGN viewed edge-on through the optically thick torus



AGN viewed face-on

- **No previous instrument has employed focusing in the Hard X-ray band**
- **Multilayer coatings and hard X-ray pixelated detectors to increase high energy response**
- **Dramatic sensitivity improvements will be achieved**

Key Questions to Understanding the Evolving Universe



The life cycles of matter in an evolving Universe

When were clusters of galaxies formed and how do they evolve?

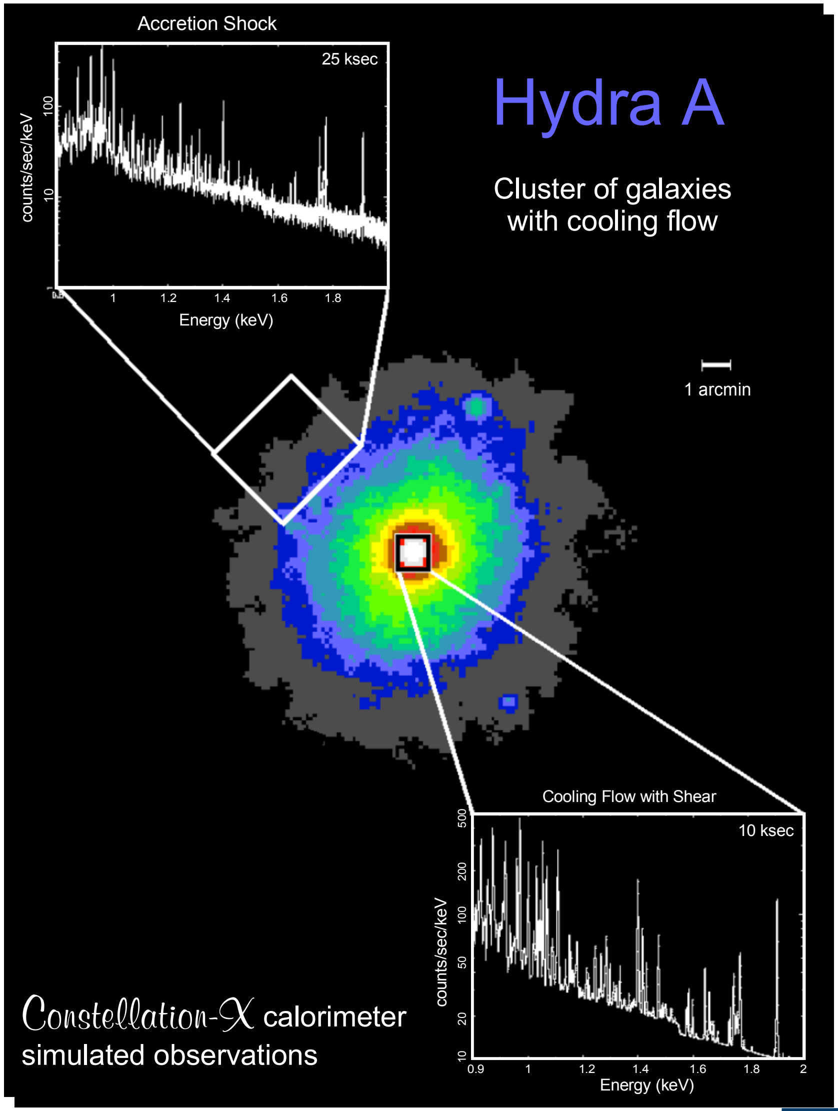
Where are the "missing baryons" in the local Universe?

How are matter and energy exchanged between stars and the Interstellar Medium and how is the Intergalactic Medium enriched?

What is the role of magnetic fields in stellar evolution?

When Were Clusters of Galaxies Formed and How Do They Evolve?

Clusters of galaxies are the largest and most massive objects known



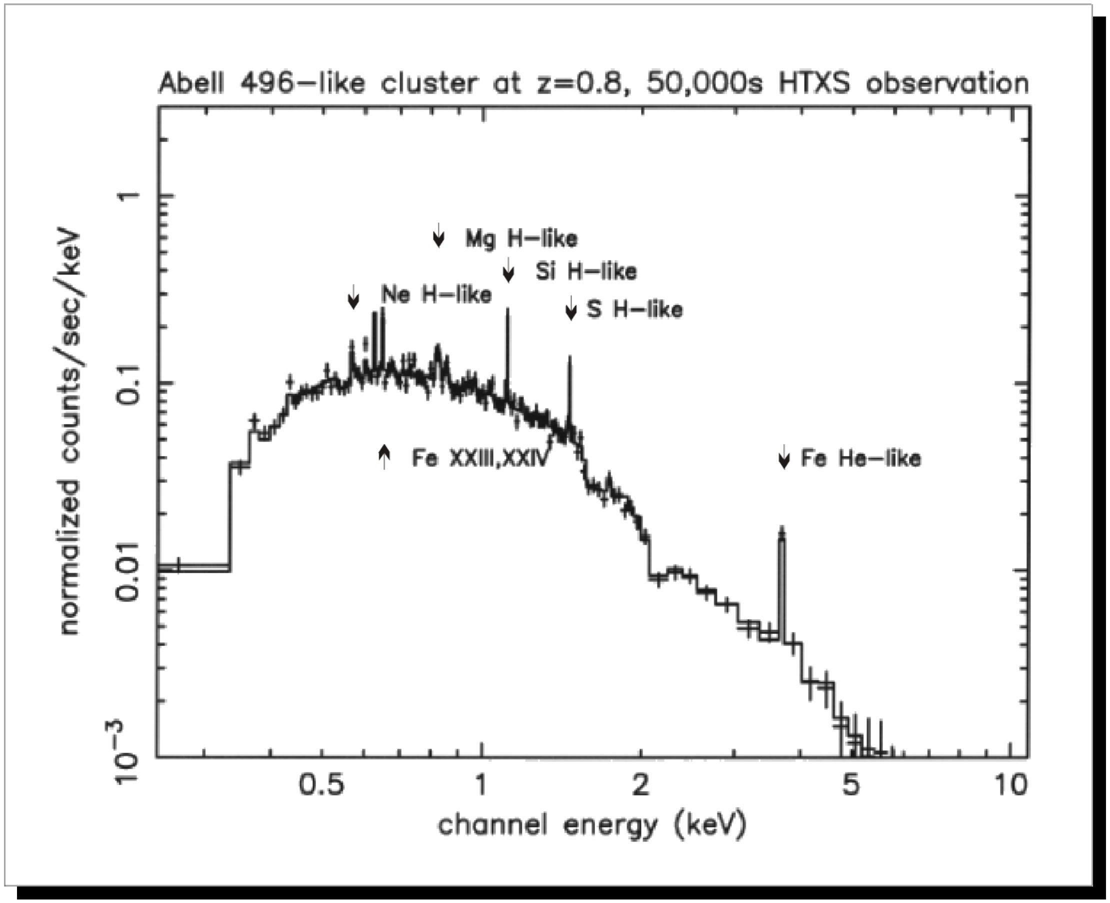
Baryon content of Universe is dominated by hot X-ray emitting plasma

Constellation-X observations of clusters essential for understanding structure, evolution, and mass content of the Universe

- Observe epoch of cluster formation and determine changes in luminosity, shape, and size *vs* redshift
- Measure abundances of elements from carbon to zinc, globally mapping generation and dissemination of seeds for earth-like planets and life itself
- Map velocity profiles, probing dynamics and measuring distributions of luminous and dark matter

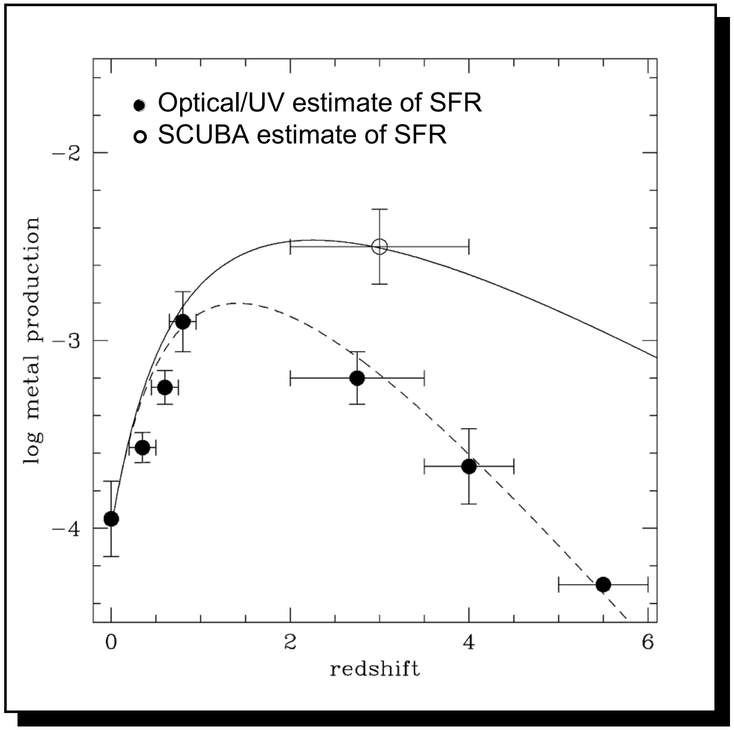
Constellation-X Observations of High z Clusters

A simulated 50,000 s exposure of a cluster at z=0.8:

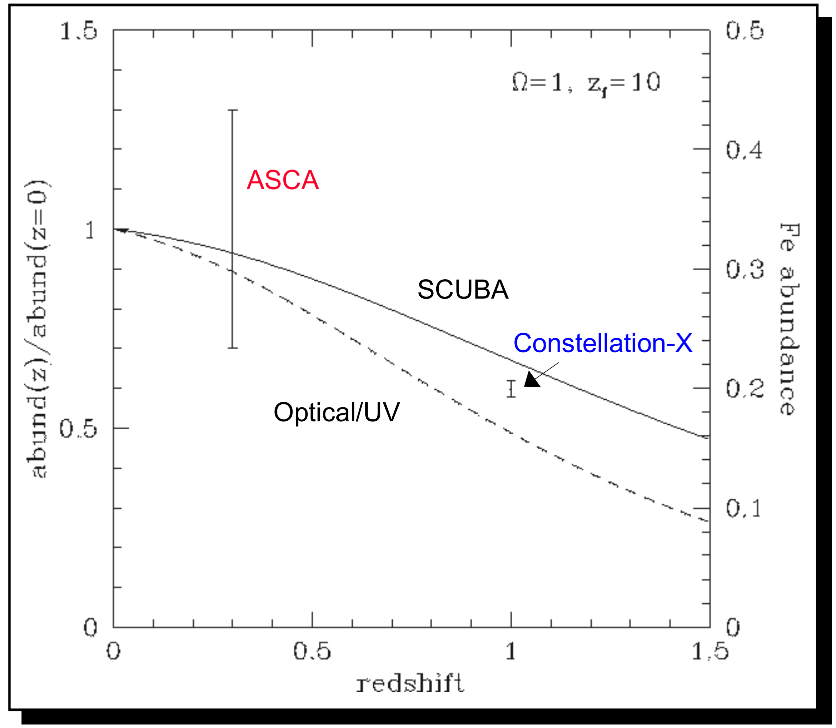


- Luminosity of 3.5 x 10^{44} ergs/s
- Temperature of 4 keV
- Type II abundance distribution
- Abundances are determined to 10% accuracy for Si, S, and Fe and 20% for Ne and Mg

Star Formation History in the Universe



SFR Rate vs z



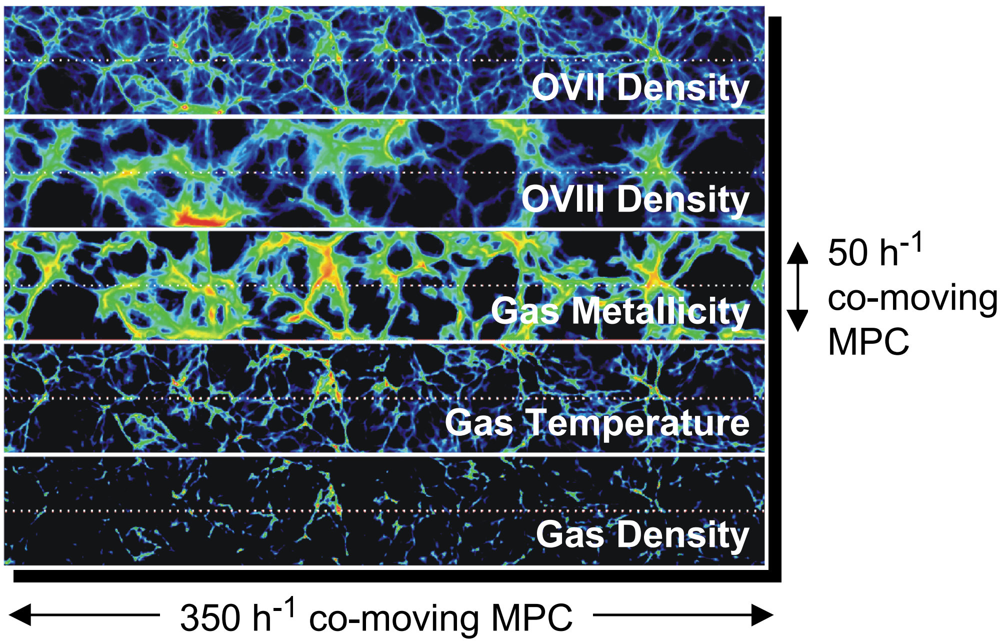
Evolution of ICM Metallicity vs z

- Past metal production and star formation rate (SFR) is imprinted on the intracluster medium (ICM) gas.
- Constellation-X measurement of ICM metallicity out to redshifts beyond 2 will help distinguish among different star formation models.

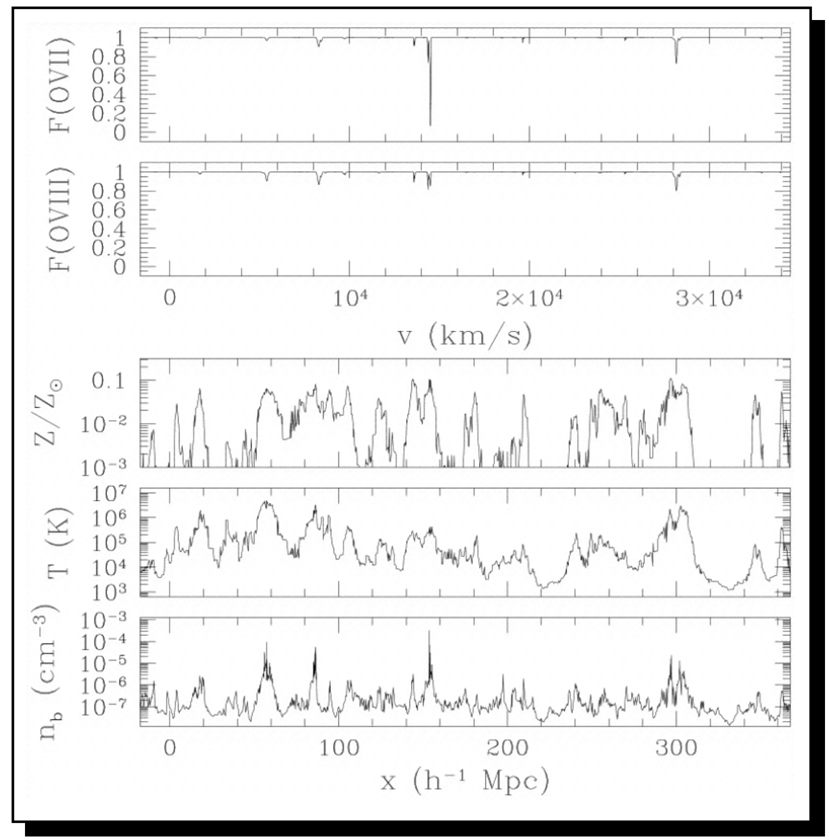
Where Are the "Missing Baryons" in the Local Universe?

At low redshifts, baryons found in stellar systems and clusters are an order of magnitude lower than that predicted from nucleosynthesis and Lyman α forest.

Numerical simulations predict most baryons found in Ly α forest at low redshift reside in the IGM with $T \sim 10^5$-10^7 K



Slice of a numerical simulation of IGM at low redshift (Hellsten, Gnedin, Miralda-Escude, 1998)



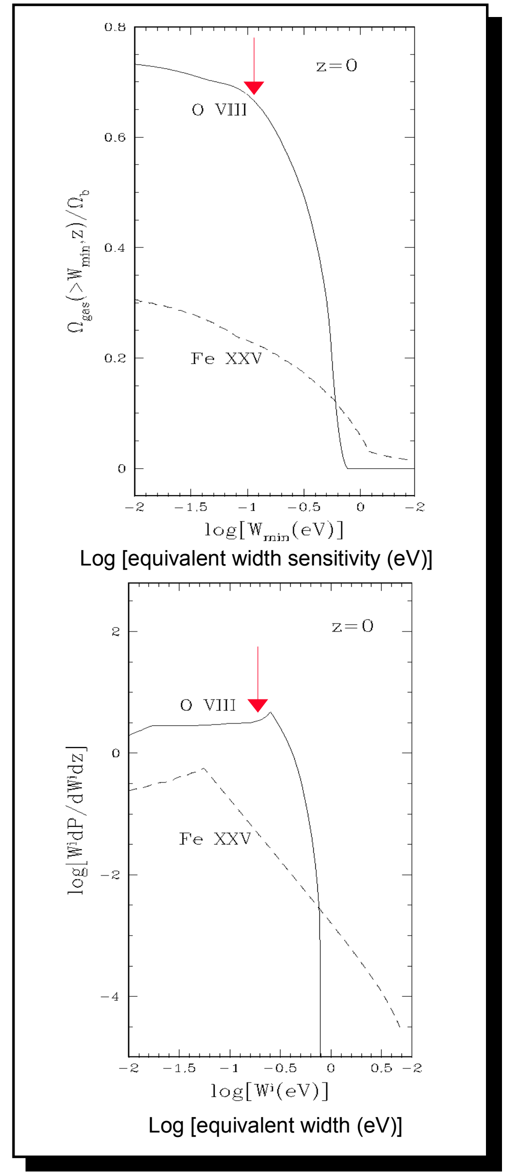
Random line-of-sight through the slice from numerical simulation figure.

Where Are the "Missing Baryons" in the Local Universe?

- The presence of the hot IGM gas can be "detected" via high resolution spectroscopy revealing absorption lines of IGM metals against the spectrum of background quasars

- Constellation-X will be able to probe up to 70% of the hot gas in groups and clusters of galaxies at low redshifts through OVIII resonant absorption

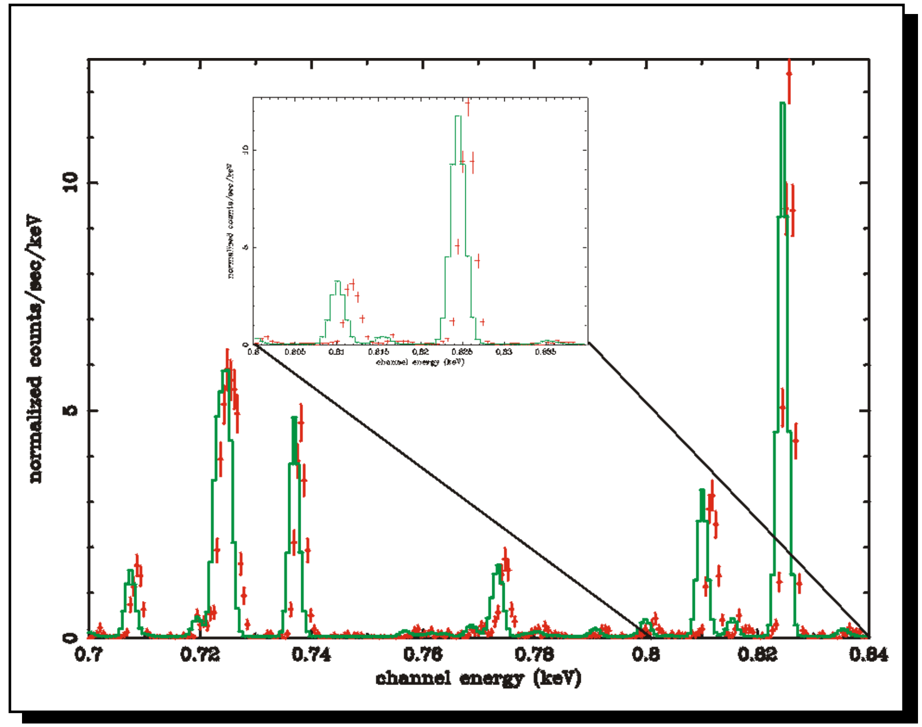
- Arrow shows sensitivity S/N = 5 after 2 x 10^5 s for QSO with 8 x 10^{-12} erg cm^{-2} s^{-1}



From Perna and Loeb (1998).

Dark Matter Distribution in Spiral Galaxies

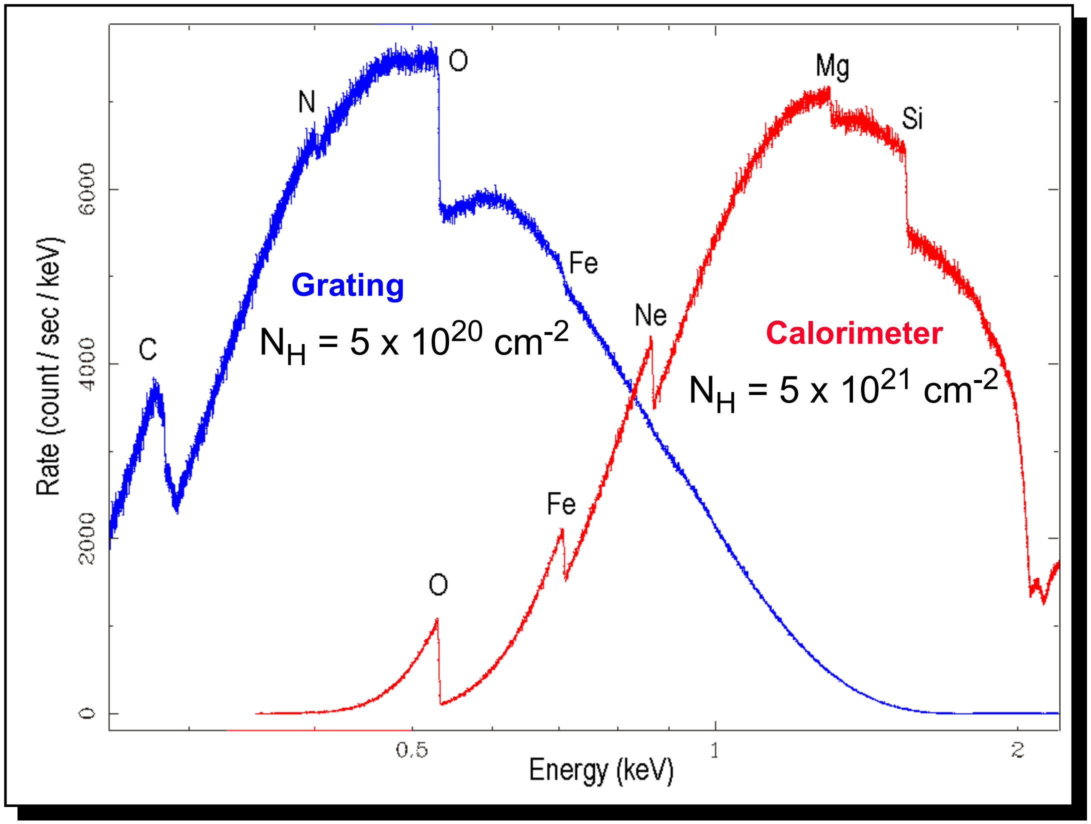
- Rotation curves of cold gas and stars prove existence of dark matter halos. Since stars and gas are confined to the plane of the galaxy, the rotation curves probe only <u>2D distribution</u> of dark matter.
- By measuring the T and r distribution of hot gas surrounding the galaxy, as well as its rotational velocity, the <u>3D distribution</u> of dark and luminous matter in the galaxy can be uniquely determined.
- Expected rotation velocities are ~ 300 km s^{-1}. For kinematic studies, line centroids must be measured to ~ 1 eV, well within Constellation-X capabilities.



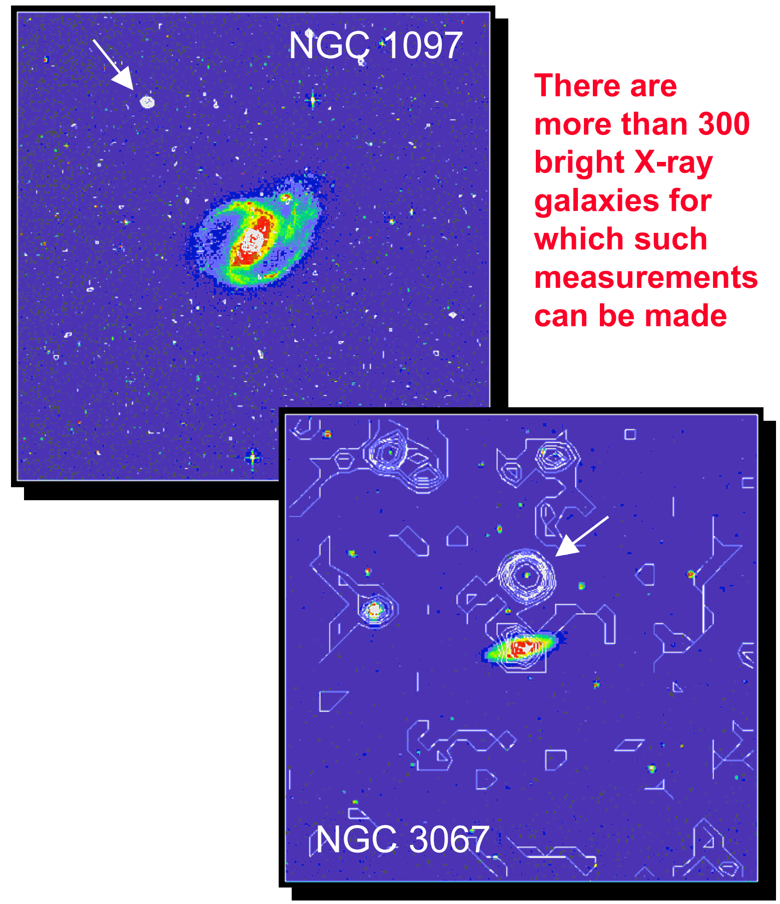
A 50 ks simulated observation of the hot halo gas in the edge-on spiral galaxy NGC 891. The solid line shows gas model shifted by 600 km/s (assuming halo circular velocity of 300 km/s based on disk measurements).

Abundances in Galactic Halos

- Galactic halo abundances can be accurately measured via K or L shell absorption of X-rays against background quasars
- Unlike the UV, X-ray measurements are independent of ionization state

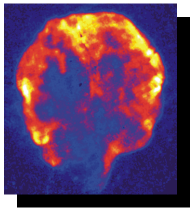


Spectra of two typical quasars absorbed through two different hydrogen column densities in the ISM

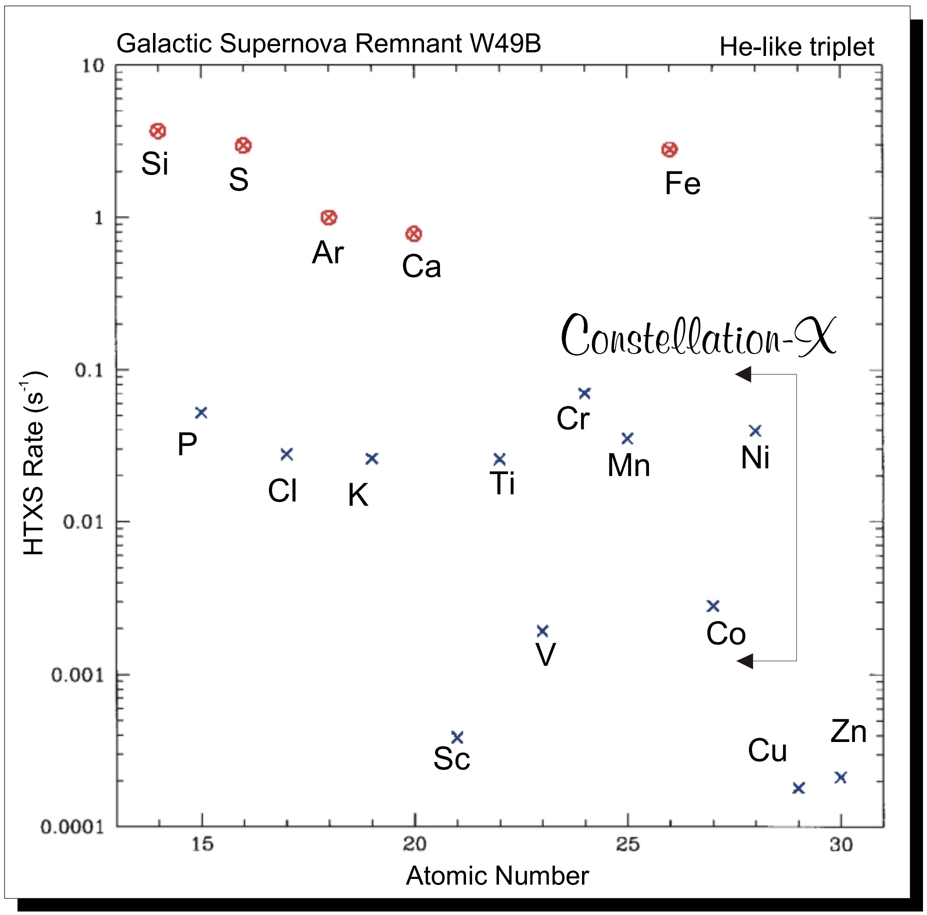


There are more than 300 bright X-ray galaxies for which such measurements can be made

Constellation-X Measurements of Chemical Enrichment



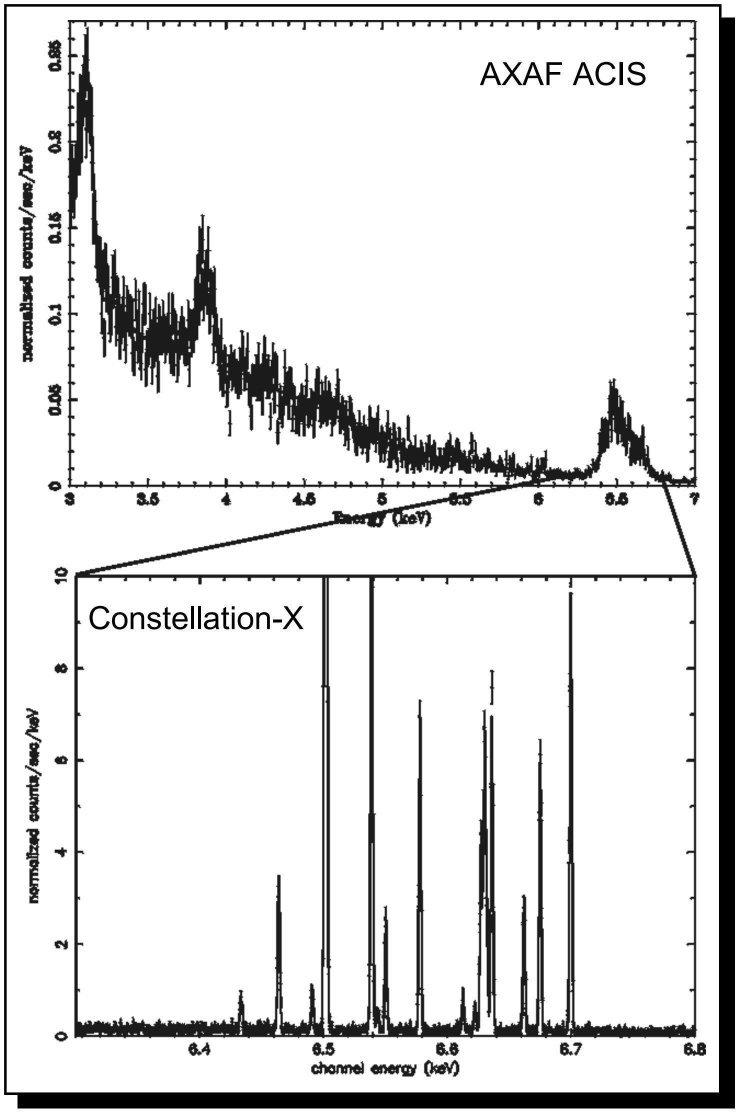
Stellar evolution in galaxies drives the chemical evolution of the Universe.

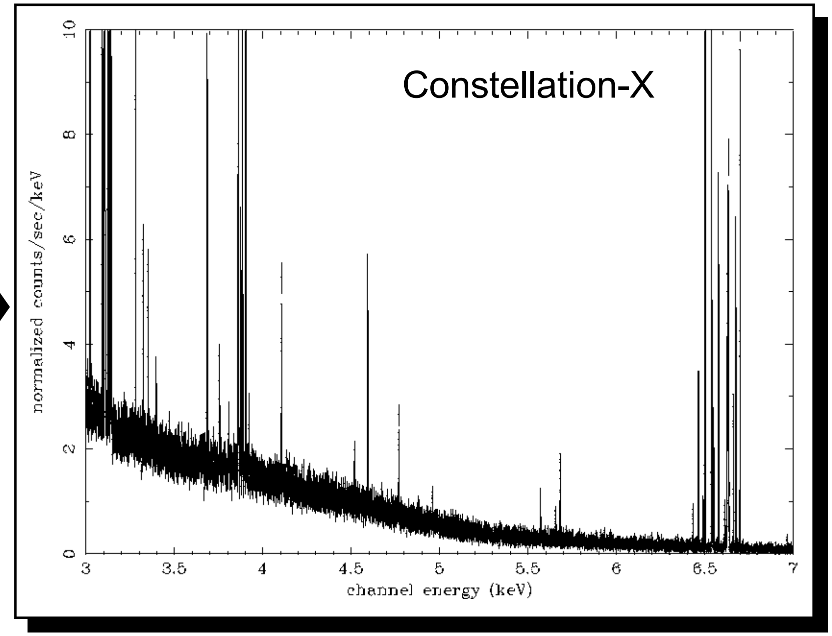


- Determine the abundances and velocity distribution of even- and odd-Z elements from Carbon to Zinc in extended supernova remnants.
- Significant detection of odd-Z elements achieved by Constellation-X in less than 20 ks will help us understand the processes that lead to their production (beyond the α-processes).
- Detection of the Ti-Cr-Mn-Ni (near iron group) will help us understand Type Ia supernovae.

SNR in External Galaxies

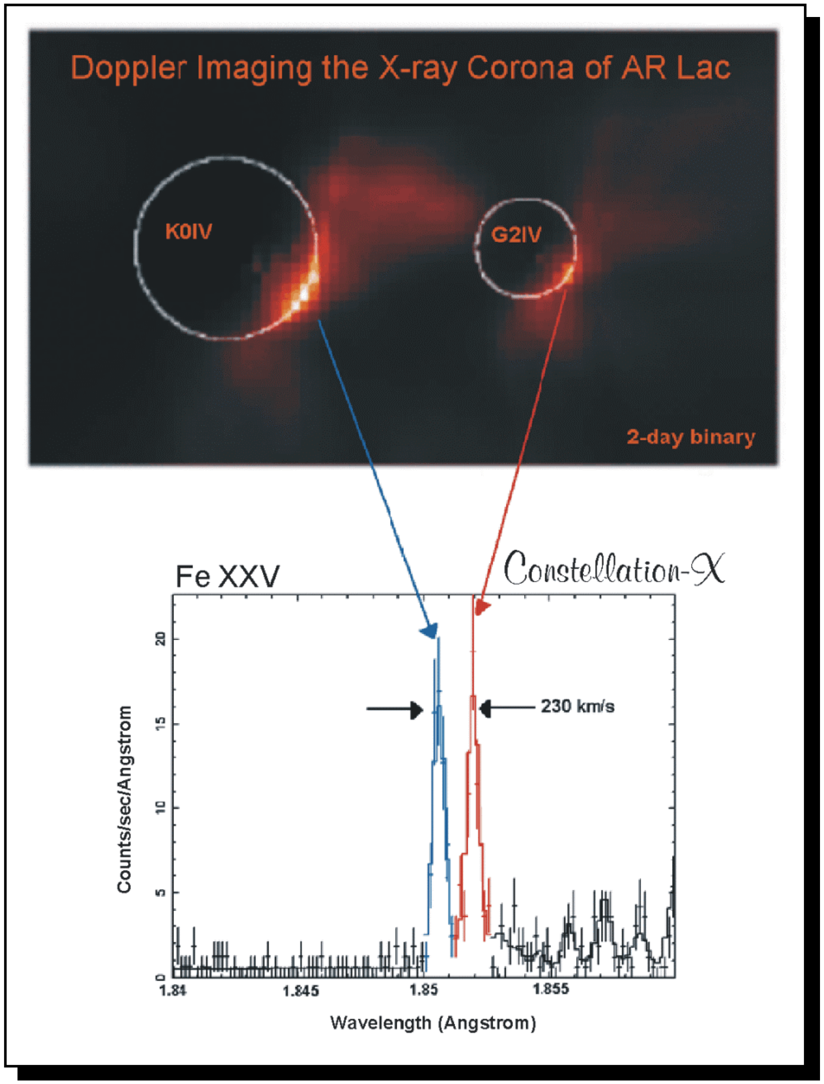
SNR N103B in Magellanic Cloud





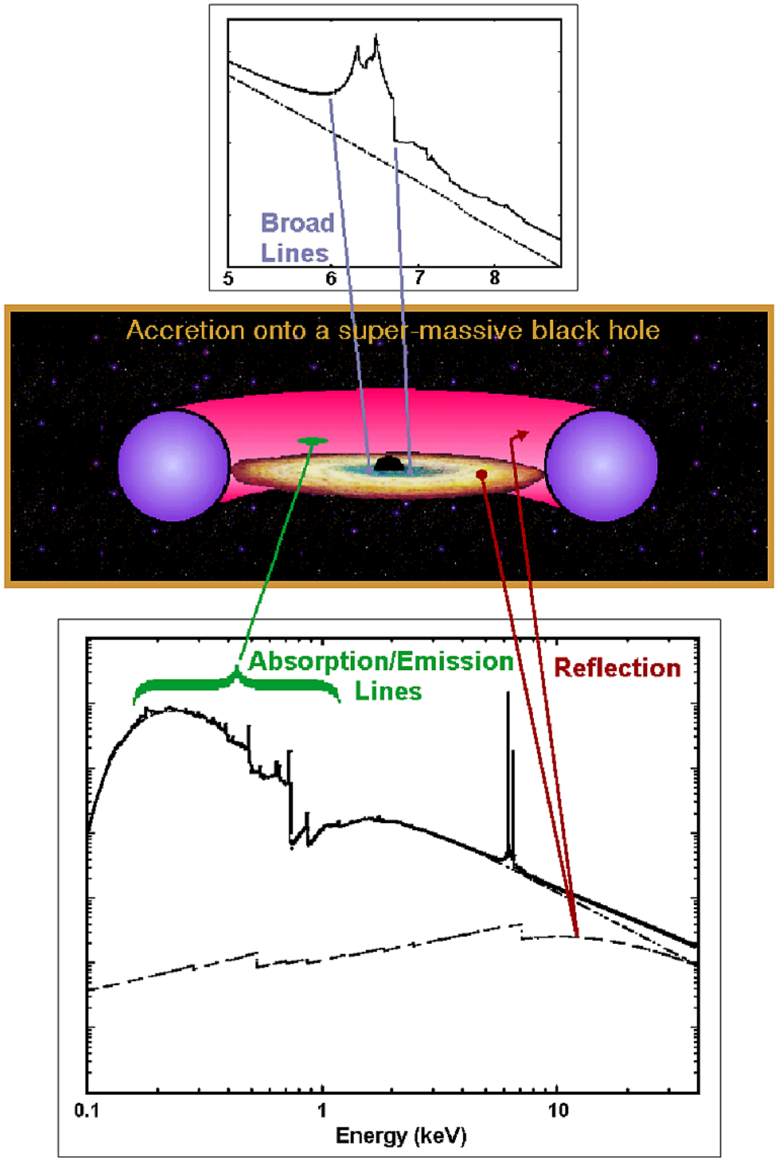
- Type supernova remnants using high resolution spectra of remnants in external galaxies located out to the distance of the Virgo Cluster.
- Use non-thermal signatures to identify sites of cosmic ray acceleration in young supernova remnants.

Constellation-X Observations of Stellar Coronae



- Plasma spectroscopy and Doppler imaging of coronal activity in stars
- Study magnetic reconnection, mass motion, densities, and abundances in stellar flares
- Investigate the formation and evolution of magnetic dynamos in young and pre-main sequence stars in molecular clouds
- Obtain high resolution spectra of stellar coronae from a wide range of luminosity
- Obtain high quality spectra of active stars such as RS CVn and Algol systems out to ~30 kpc

Key Questions to Understanding the Ultimate Limits of Gravity



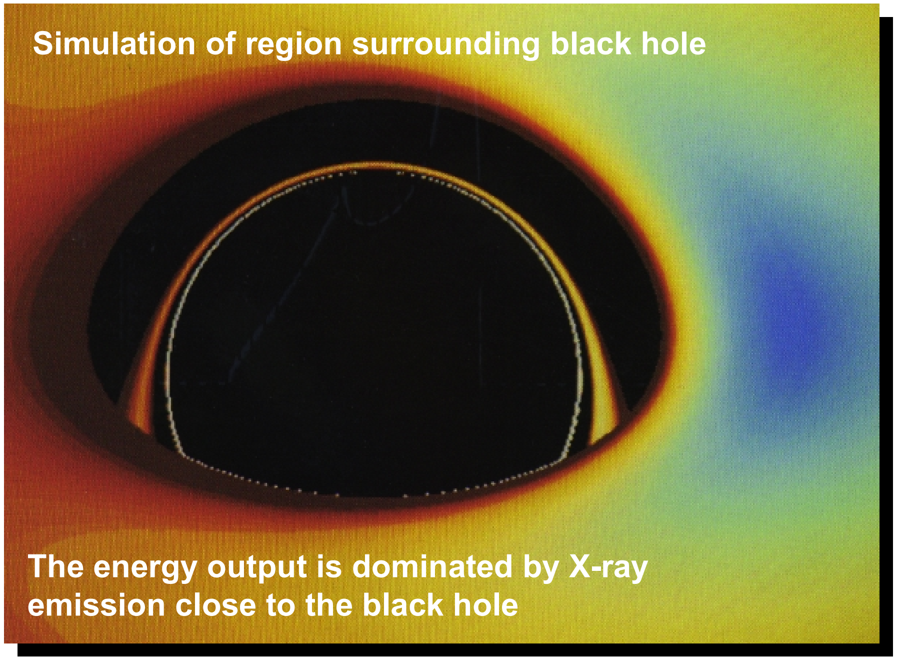
How can we use observations of black holes to test General Relativity?

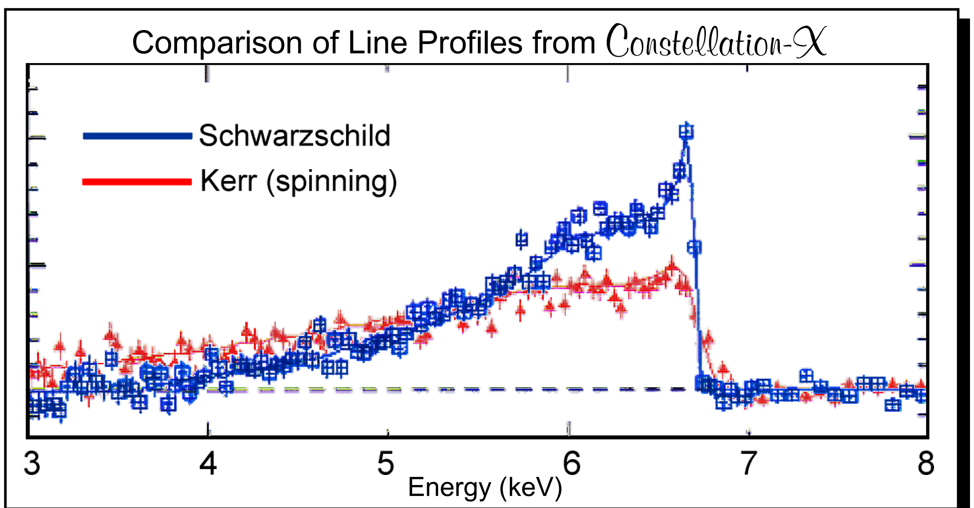
What is the total energy output of the Universe?

What roles do supermassive black holes play in galaxy evolution?

How does gas flow in accretion disks and how do cosmic jets form?

How Can We Use Observations of Black Holes to Test General Relativity?

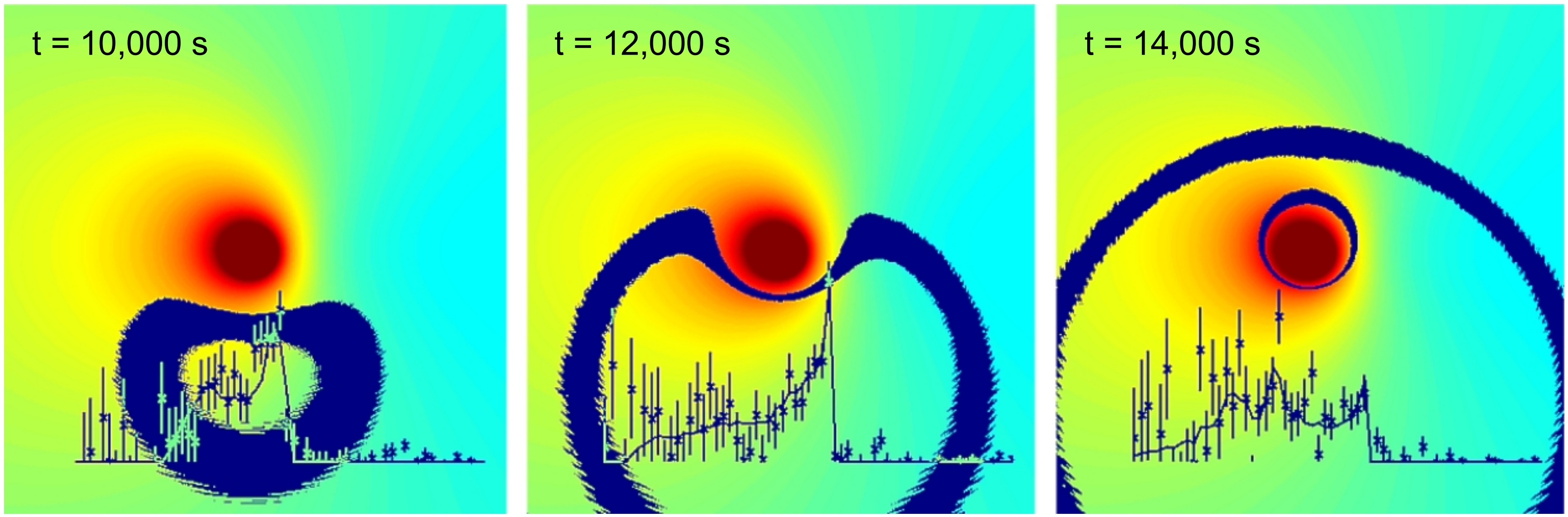




- **Active galactic nuclei and quasars are powered by accretion of matter onto supermassive black holes**
- **X-rays are produced near the black hole event horizon and probe 100,000 times closer to the black hole than HST**
- **Relativistically broadened iron K α lines will probe the inner sanctum near black holes, testing GR in the strong gravity limit**
- *Constellation-X* **will determine black hole mass and spin using iron K α lines**
  - Spin from the line profiles
  - Mass from the time-linked intensity changes for line and continuum emission

Constellation-X

Reverberation Mapping in AGN

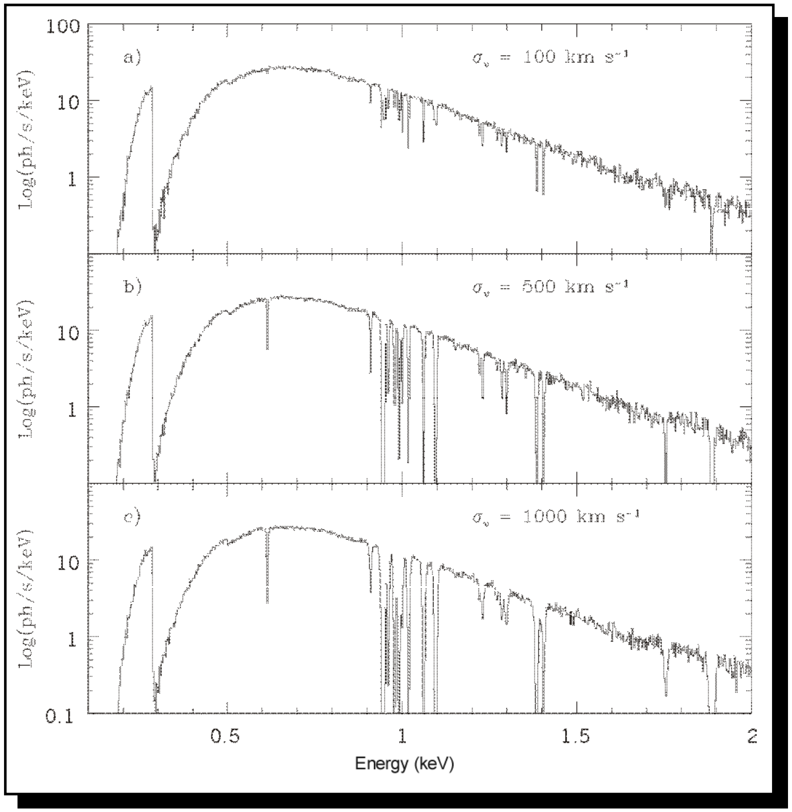


Theoretical "images" of an accretion disk around a maximally rotating 10^8 solar mass black hole and the echoes of a propagating flare. The corresponding Constellation-X line profiles (1000 s simulation) are also shown.

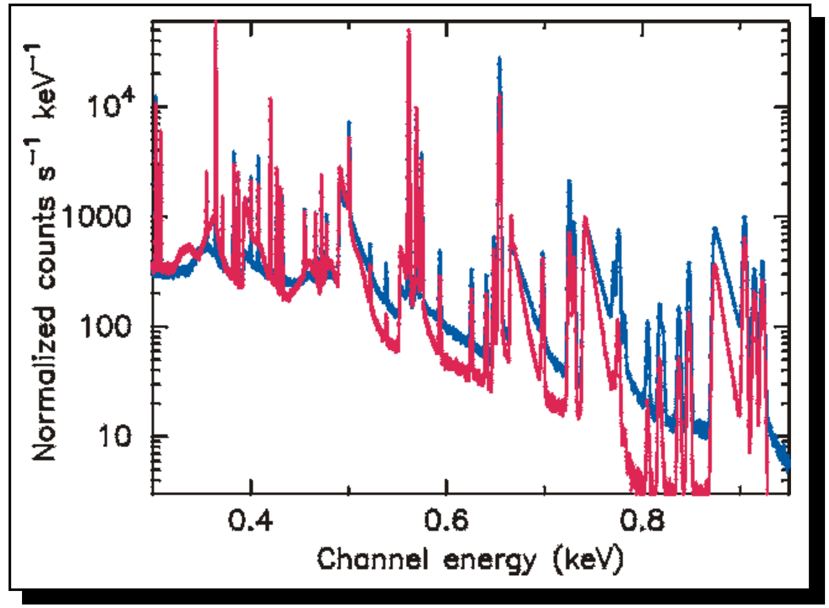
- Map out the immediate environment of the black hole
- Probe the accretion disk motion and the strong gravitational field
- Determine the dependence of mass accretion rate on luminosity and redshift

☑ *How can we use observations of black holes to test General Relativity?*
☐ *What is the total energy output of the Universe?*
☐ *What roles do supermassive black holes play in galaxy evolution?*
☑ *How does gas flow in accretion disks and how do cosmic jets form?*

The AGN Environment



A 20 ks Constellation-X exposure of the NLSy1 galaxy IRAS 13224 with different cloud dispersion velocities for the absorbing medium.

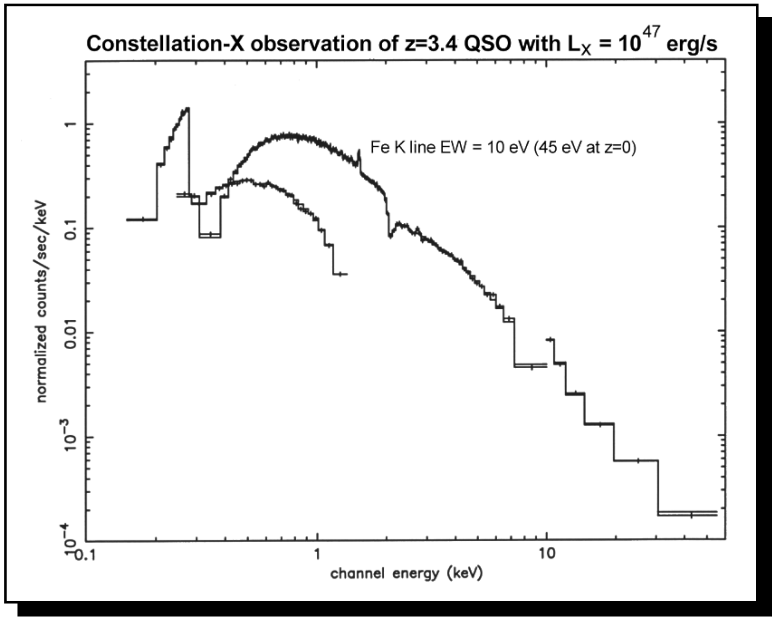


Emission features from an ionized absorbing medium.

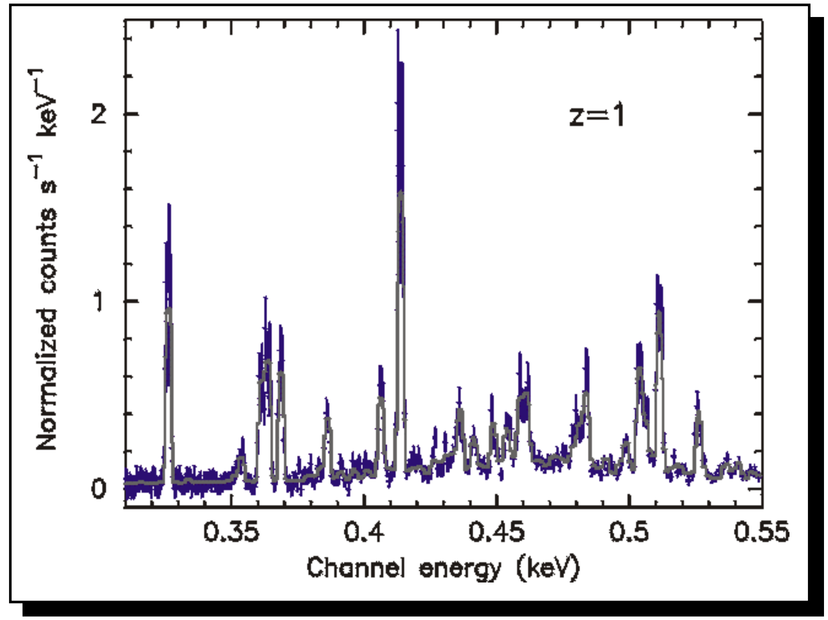
- What is the composition and geometry of the accretion flow?
- How is material transported to the centers of AGN?

☐ *How can we use observations of black holes to test General Relativity?*
☐ *What is the total energy output of the Universe?*
☐ *What roles do supermassive black holes play in galaxy evolution?*
☑ *How does gas flow in accretion disks and how do cosmic jets form?*

AGN at High z



Constellation-X grating, calorimeter, and HXT simulation of a quasar at z = 3.2.

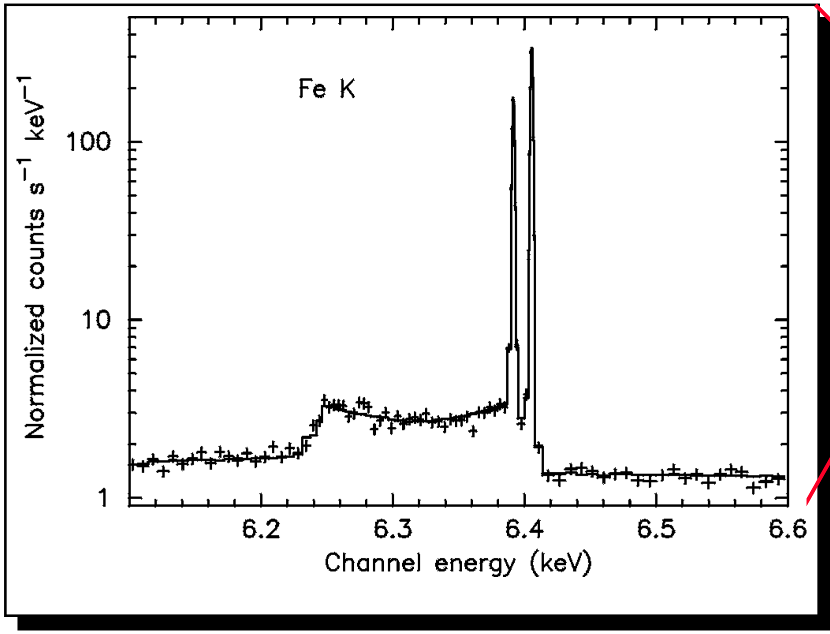


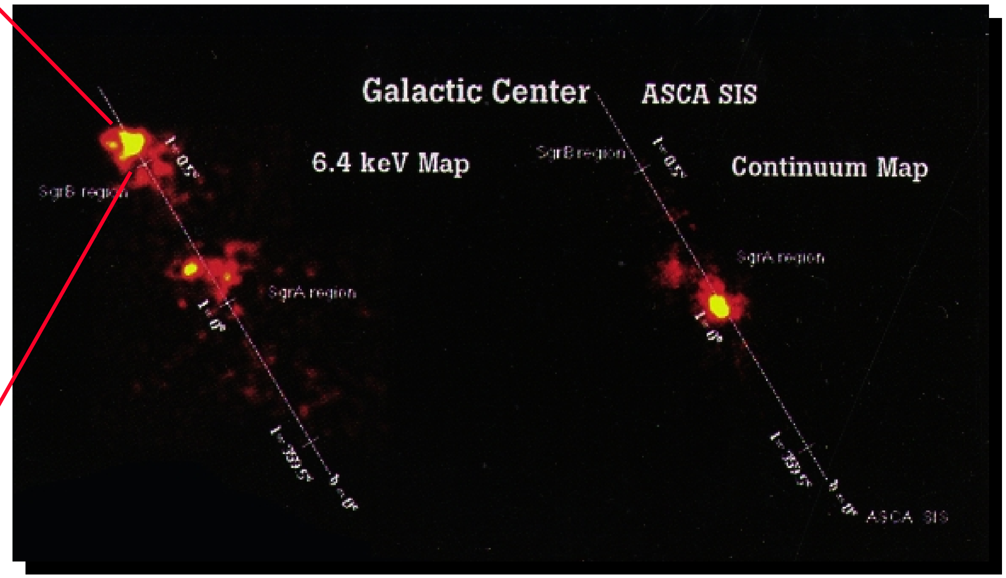
A 100 ks grating simulation of a starbursting Seyfert galaxy at z = 1.

- Study faint AGN populations
- Study the role black holes play in galaxy evolution
- Examine the starburst-AGN connection

☐ *How can we use observations of black holes to test General Relativity?*
☑ *What is the total energy output of the Universe?*
☑ *What roles do supermassive black holes play in galaxy evolution?*
☐ *How does gas flow in accretion disks and how do cosmic jets form?*

The Galactic Center Region



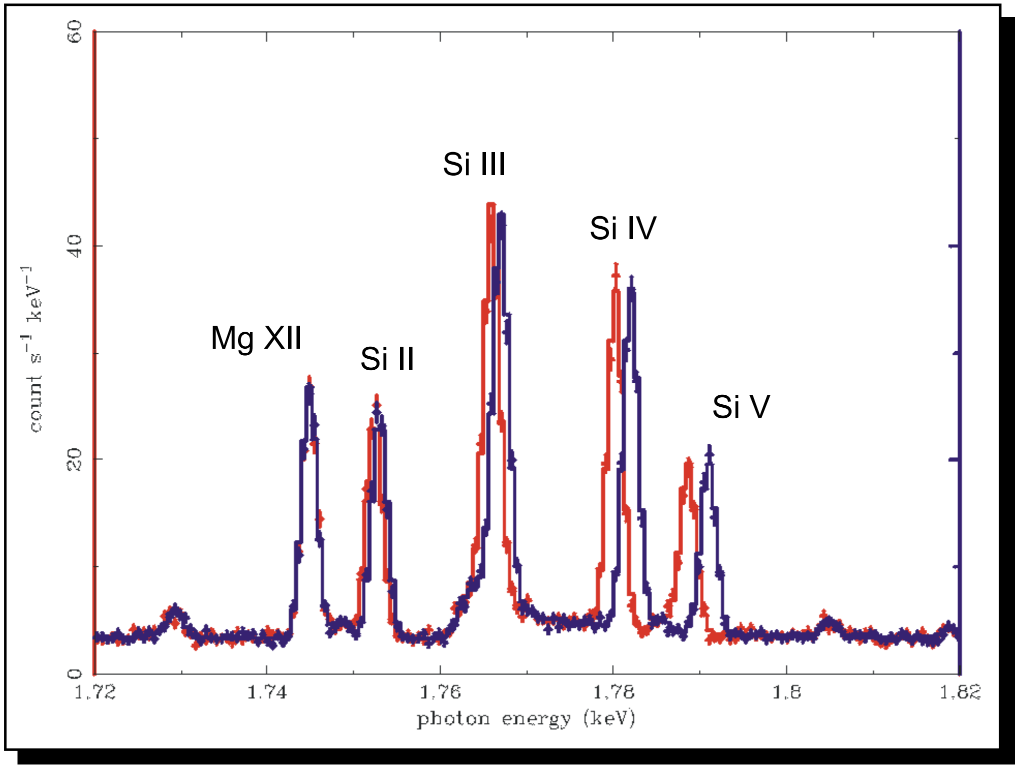


Twenty ks simulation of Galactic center emission at ~ 6.4 keV (reprocessed from an earlier epoch when the nucleus was X-ray bright)

- Observe the fossil “footprint” of an active nucleus
- Measure ionization state, temperature, and density of the ISM
- Determination of H to He abundance from 10 eV difference in energy gap

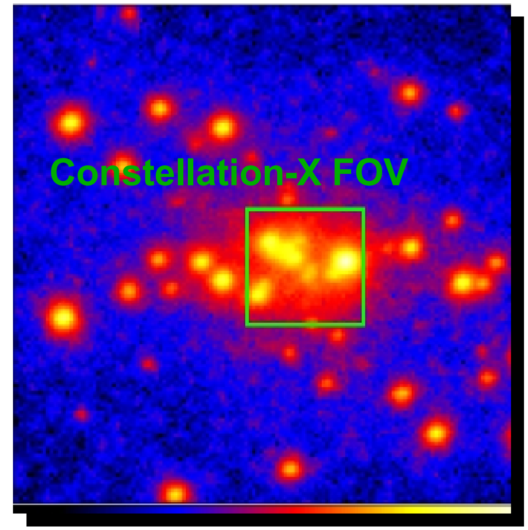
☐ *How can we use observations of black holes to test General Relativity?*
☑ *What is the total energy output of the Universe?*
☑ *What roles do supermassive black holes play in galaxy evolution?*
☐ *How does gas flow in accretion disks and how do cosmic jets form?*

X-ray Binaries



A 10 ks Constellation-X simulation of Si K emission lines formed in a stationary atmosphere (red) vs an accelerating stellar wind (blue). The velocity/ionization relationship in the accelerating emission line region is linear with velocities of 100, 200, 300, and 400 km/s for Si II, III, IV, and V, respectively.

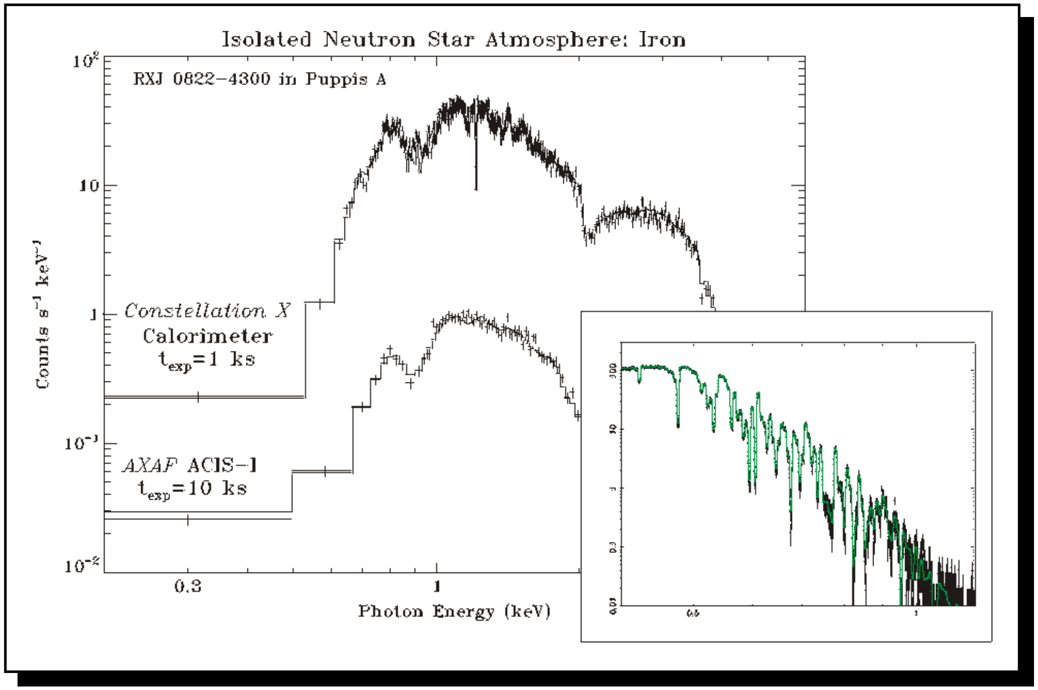
Constellation-X image of M31



- Probe the physics of the emitting/accreting matter
- Track the radial velocities
- Obtain dynamical information for binary systems that have no optical counterpart
- Stationary atmospheres versus accelerating stellar winds
- Observe X-ray binaries in other galaxies out to ~ 10 Mpc

☑ *How can we use observations of black holes to test General Relativity?*
☐ *What is the total energy output of the Universe?*
☐ *What roles do supermassive black holes play in galaxy evolution?*
☐ *How does gas flow in accretion disks and how do cosmic jets form?*

Isolated Neutron Stars

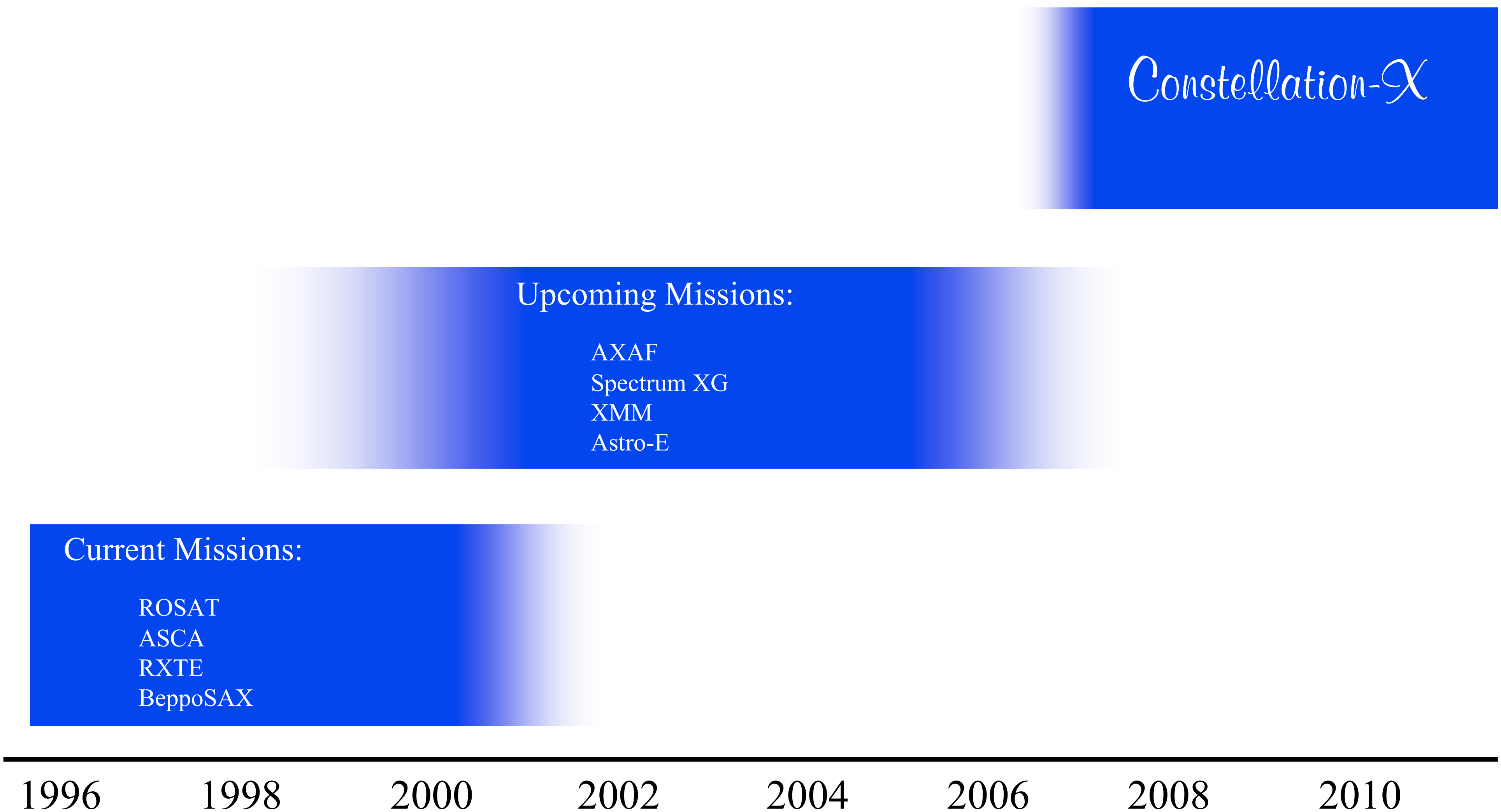


Simulated neutron star spectrum assuming solar iron abundance (main panel) and a magnetic atmosphere (inset).

- Study physics in extreme environments
- Measure the surface gravity via redshift and pressure broadening of spectral lines
- Trace evolution through changes in chemical composition
- Infer the equation of state of neutron stars
- Investigate neutron star atmospheres

X-ray Observatories Timeline

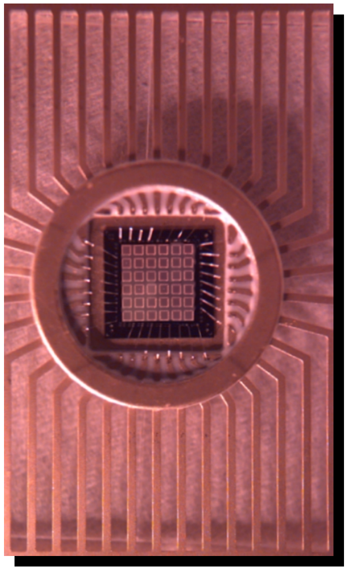
Current X-ray astronomy missions have expected 5-10 year lifetimes.



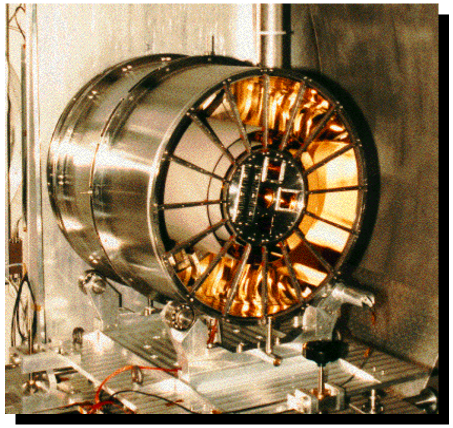
Constellation-X Organization Chart

- **Project Formulation Manager**
  Jean Grady - GSFC
  - **Facility Science Team Chair:**
    Harvey Tananbaum - SAO
  - **Project Scientist**
    Nicholas White - GSFC
  - **Systems Engineers**
    William Podgorski - SAO
    Govind Gadwal/Robin Mauk - GSFC
  - **Mission Scientists**
    Frank Marshall - GSFC
    Jay Bookbinder - SAO
  - **Technology Development**
    Robert Rasche - SAO
    - **Spectroscopy X-ray Telescope**
      Leon Van Speybroeck - SAO
      - **SXT Replicated Shells**
        Stephen O'Dell - MSFC
      - **SXT Replicated Segments**
        Robert Petre - GSFC
    - **X-ray Calorimeter**
      Richard Kelley - GSFC
    - **Cryogenics**
      Stephen Castles - GSFC
    - **Extendible Optical Bench**
      Oren Sheinman - GSFC
    - **Hard X-ray Telescope**
      Fiona Harrison - CalTech
    - **CCD/Grating**
      Steve Kahn - Columbia
  - **Mission Study**
    Jean Grady - GSFC
    (Acting)
    - **C&DH**
      Philip Luers - GSFC
    - **Mechanical**
      Oren Sheinman _ GSFC
    - **ACS**
      Alan Reth - GSFC
    - **Flight Dynamics**
      Gregory Marr - GSFC
    - **Thermal**
      Robert Chalmers - GSFC
      Mark Freeman - SAO
    - **Optical Systems**
      William PodgorskI - SAO
      Lester Cohen - SAO

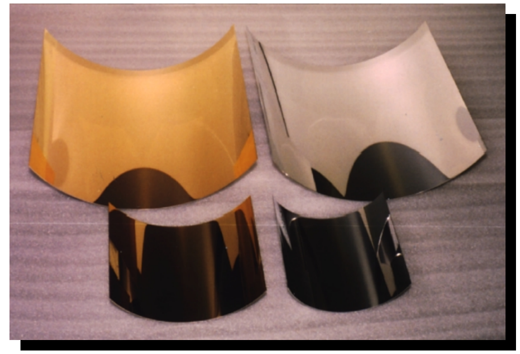
Constellation-X Technology Requirements



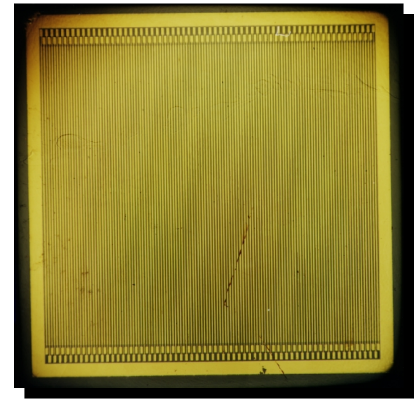
Microcalorimeters



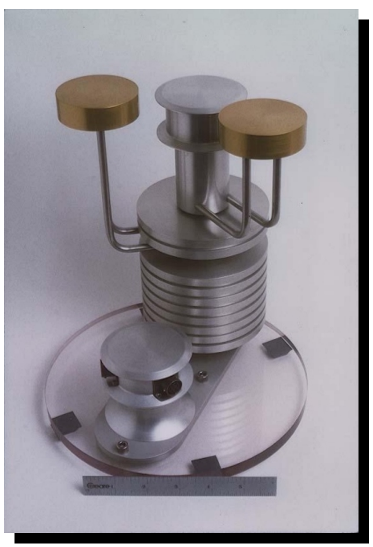
Lightweight
X-ray Optics



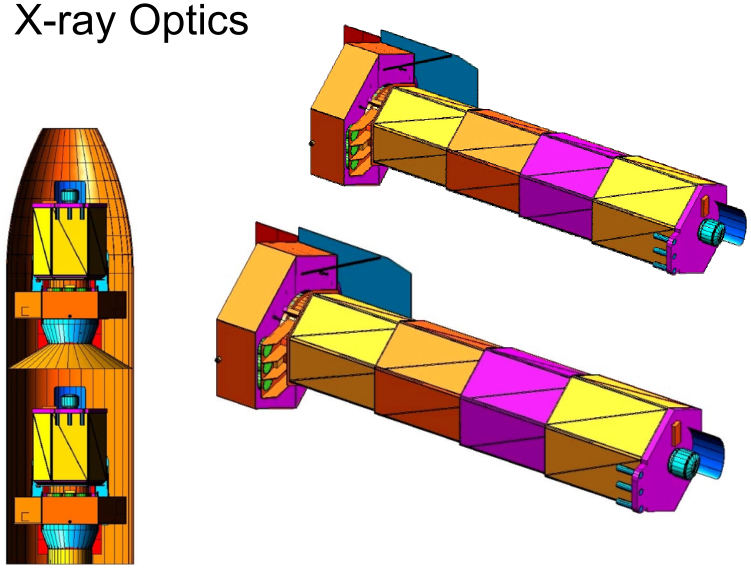
Multilayer Coatings



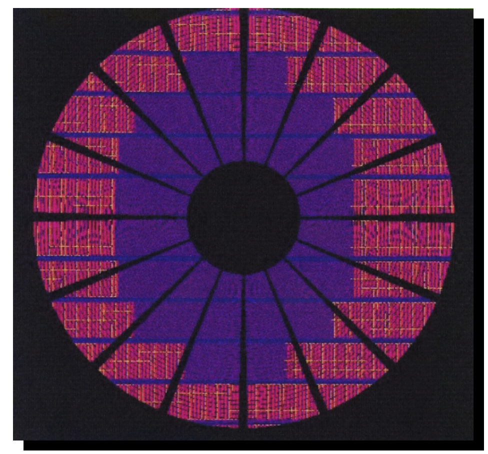
Hard X-ray Camera



Coolers



Deployable Structures

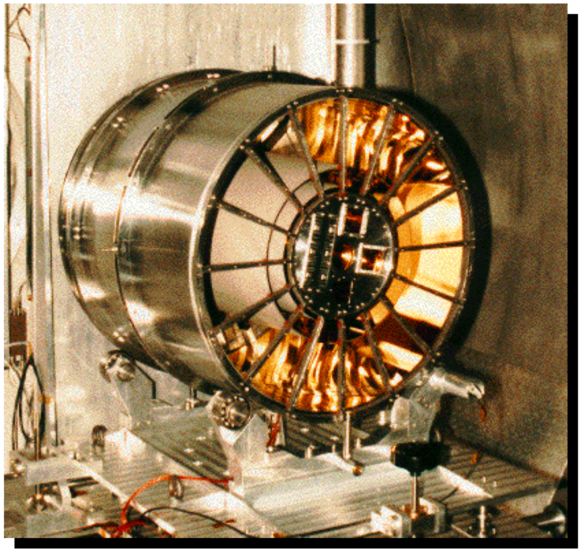


CCD/Grating

Technology Development Approach

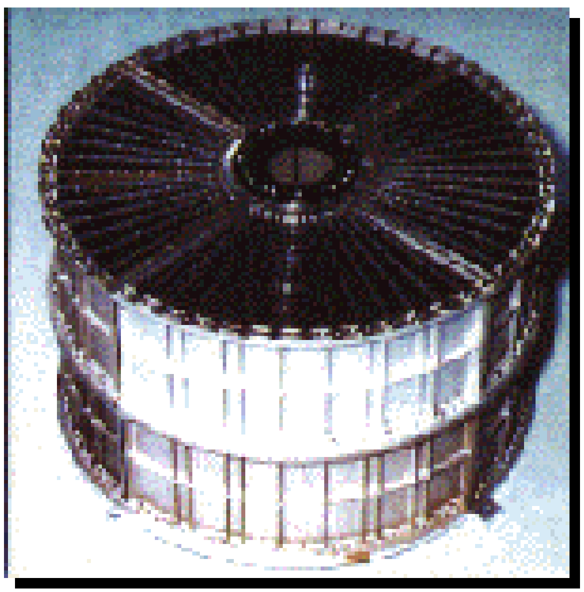
- Technology demonstrated early in the program
  - Parallel path technology development with defined selection milestones
  - Enhanced mirror technology based on replicated shells (XMM) and replicated foils (ASTRO-E)
  - Early detector and optics definition and demonstration (NRA)
  - Cooler development leverages cross-cutting technology investment (e.g., NICMOS cooler, FIRST, and NGST)
  - ADR builds on Astro-E technology
- Cost is an independent design variable
  - Cost constrained design
  - Heritage leveraged to the maximum
- Experienced management team is in place (GSFC, SAO)

SXT X-ray Mirror Design Alternatives



Replicated full-shell optics (e.g., XMM):

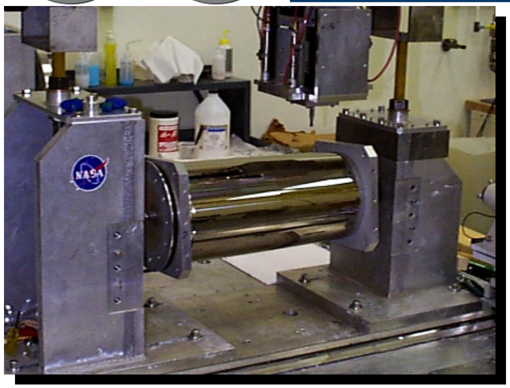
- meets 15-arcsec half-power-diameter requirement
- requires factor-of-six weight reduction
- investigate fiber-reinforced plastics and SiC and other ceramics as carriers for non-integral optics
- develop structurally reinforced, thin-walled, plated nickel alloys for integral optics

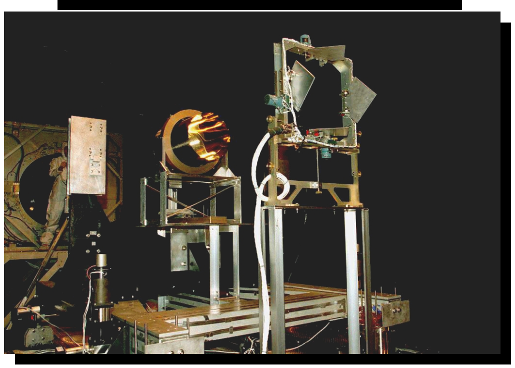


Replicated segmented optics (e.g., Astro-E):

- meets weight requirement
- requires factor-of-7 half-power-diameter reduction
- investigate stiffer substrates (metal matrix, composites, glass, stainless steel, etc.)
- develop improved mandrels and foil-alignment techniques

Progress to Date (January 1999): Replicated Shell SXT





MSFC and SAO

Shell-technology research

- Identified overcoat to effect low, controlled interfacial adhesion of replica optical surface to mandrel.
- Developed high-strength nickel alloys, to avoid plastic deformation during separation and handling.
  - Provides 10 times precision elastic limit and 3 times ultimate strength of standard nickel plating.
- Conducted successful flow tests to identify epoxy for fixing replicated optical surface to carrier.
- Abandoned hot isostatically pressed alumina; will continue to investigate plasma-sprayed ceramics.

Precision mandrels

- Installed computer-controlled polisher; let contract for plating facility for meter-class optics.
- Completed a 0.25-m-diameter mandrel (out of spec); diamond turned first 0.5-m-diameter mandrel.
- Order ed two 0.5-m-diameter mandrels from Zeiss, to be deliverd to MSFC in 1999 Summer.

Shells and optics

- Completed separation system and metrology station; received vertical long-trace profilometer.
- Received two 0.25-m-diameter fiber-reinforced-plastic carriers (out of spec) from Composite Optics.
- Received one 0.25-m-diameter silicon-carbide carrier from Morton Advanced Materials.
- Will electroform 0.25-m-diameter nickel-alloy shell in 1999 January.

Metrology and X-ray testing

- Are upgrading metrology station and vertical long-trace profilometer, to improve performance.
- X-ray tested Dornier fiber-reinforced-plastic optic; will test OAB SiC optic in 1999 January.

Osservatorio Astronomico di Brera (OAB), Italy

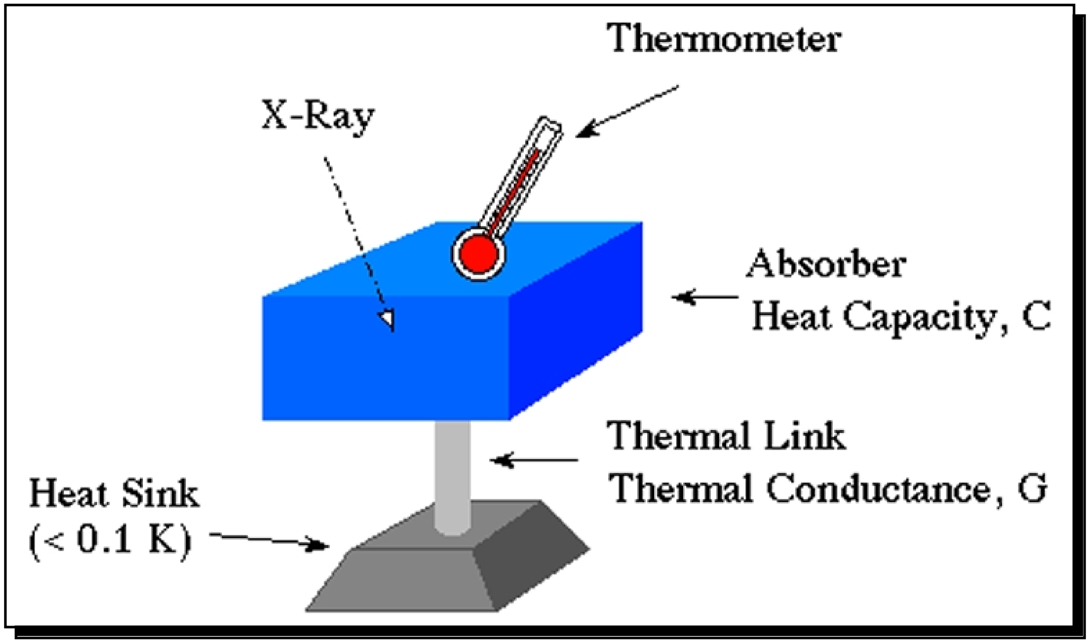
- Successfully replicated 0.6-m-diameter, 0.24-m-long silicon-carbide optic.
  - Metrology data indicates a 17-arcsec half-power diameter, to be tested at MSFC XRCF.
- Will continue development of plasma-spray alumina shells.

Progress to Date (January 1999): Replicated Segment SXT Optics

Progress to Date

- MSFC completed fabrication of metal mandrel
  - Initial replication completed
  - Demonstrated feasibility of replication
  - Polishing mandrel at GSFC to 3" finish
- Contracted for polished glass mandrel with 3" figure
  - Delivery in Spring 1999
- New foil substrates under investigation
  - Glass at Columbia University
  - Metal matrix and composites at GSFC
- Established multi-disciplinary housing engineering team
  - Investigating fixturing, assembly, and alignment improvements

Requirements on the Constellation-X Microcalorimeter Array



A detector with 2 eV spectral resolution over the 0.3 - 12 keV band

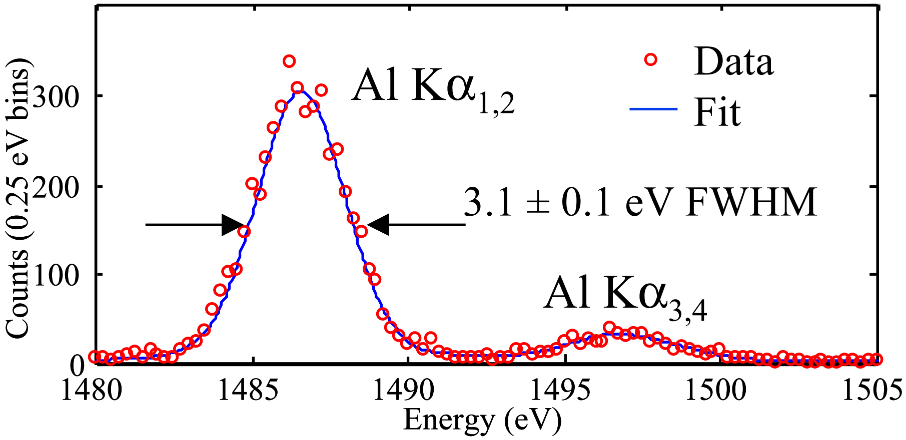
- High quantum efficiency (~99% at FeK)
- Imaging capability commensurate with mirror PSF
    - 2.5' FOV => 30 x 30 array
    - 10' FOV => 120 x 120 array
- Speed for handling counting rates of 1 kHz or more

Current capability is 7-12 eV with 10 x 10 array and maximum of ~ 100 ct/s

Technology developments required to achieve 2 eV resolution include

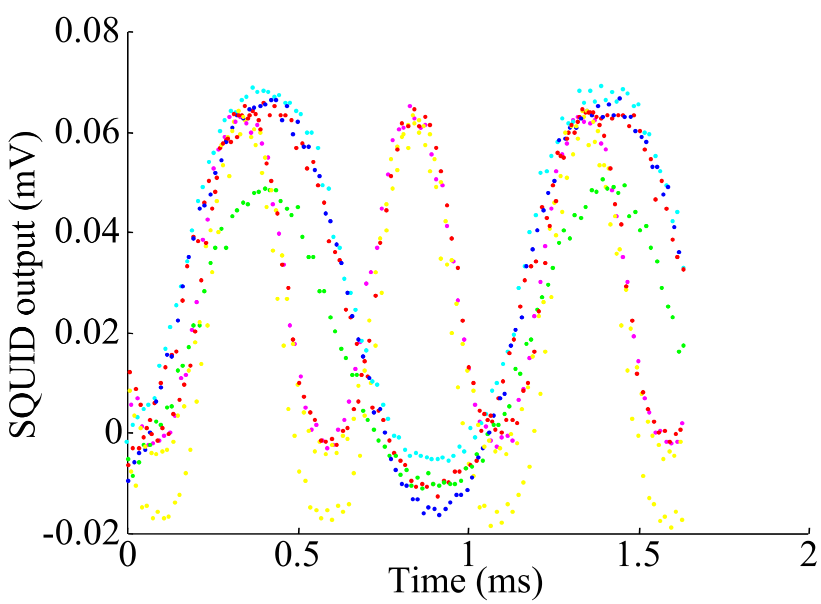
- more sensitive and faster thermometers (transition edge superconductor)
- reduce heat capacity and power dissipation of existing system

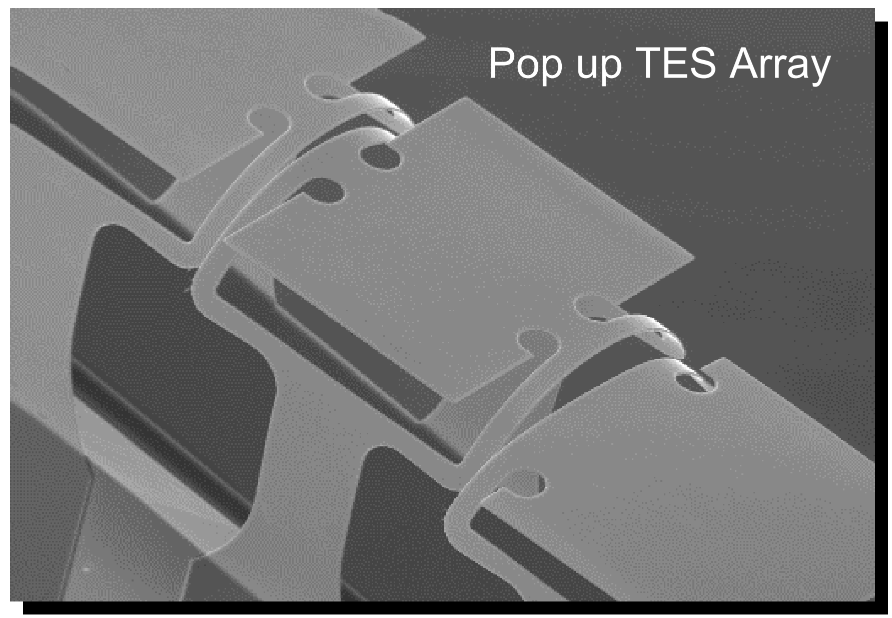
Progress to Date (January 1999): Calorimeters



Progress in TES calorimeter arrays:

- 3 eV resolution at 1.5 keV (NIST)
- SQUID multiplexing demonstrated for 8 signals at 1 MHz sampling (NIST)
- folded silicon linear array structures (the building blocks of large arrays) demonstrated on 0.2 mm pitch (GSFC)

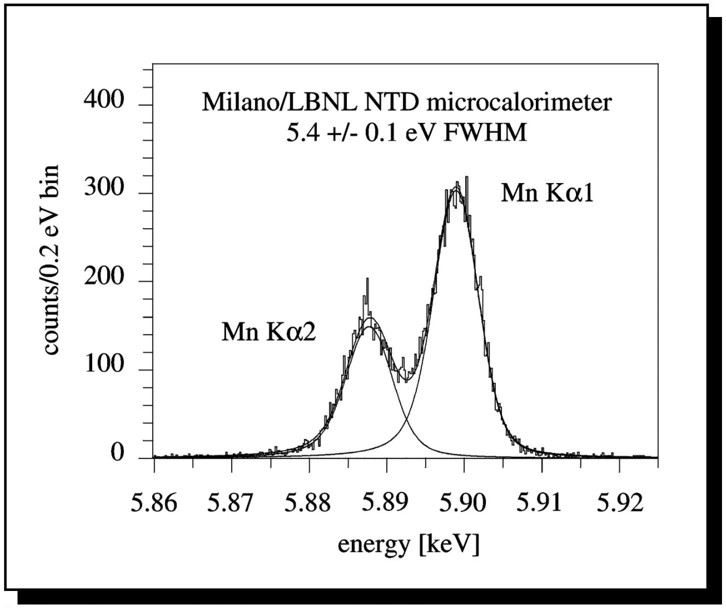


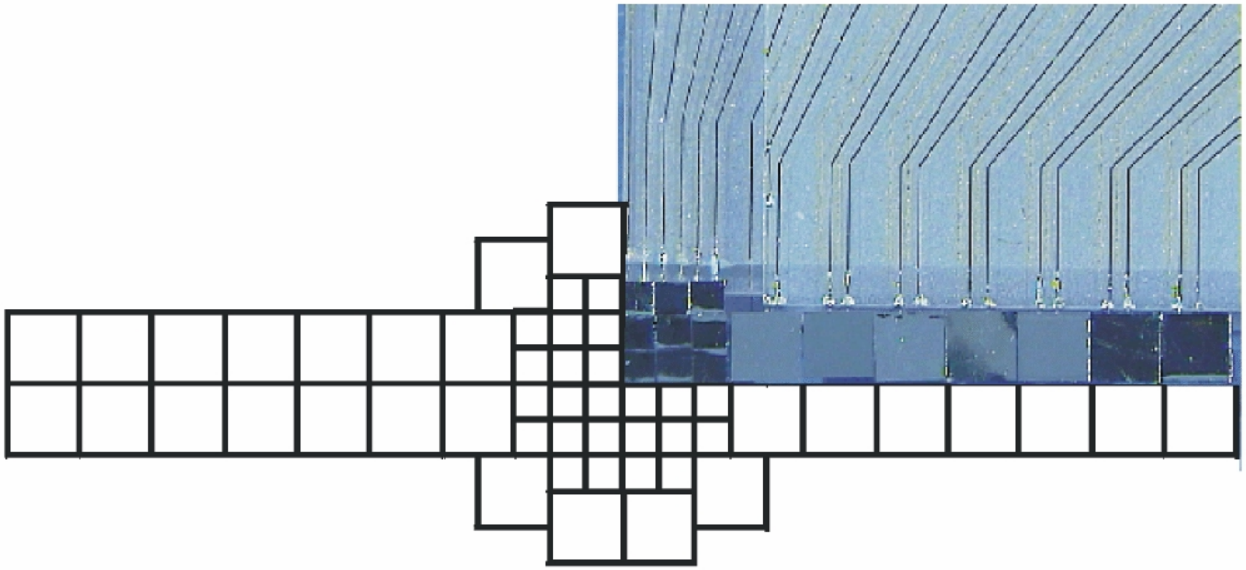


Latest Results on NTD Ge Thermistors

Progress in NTD Ge calorimeter arrays:

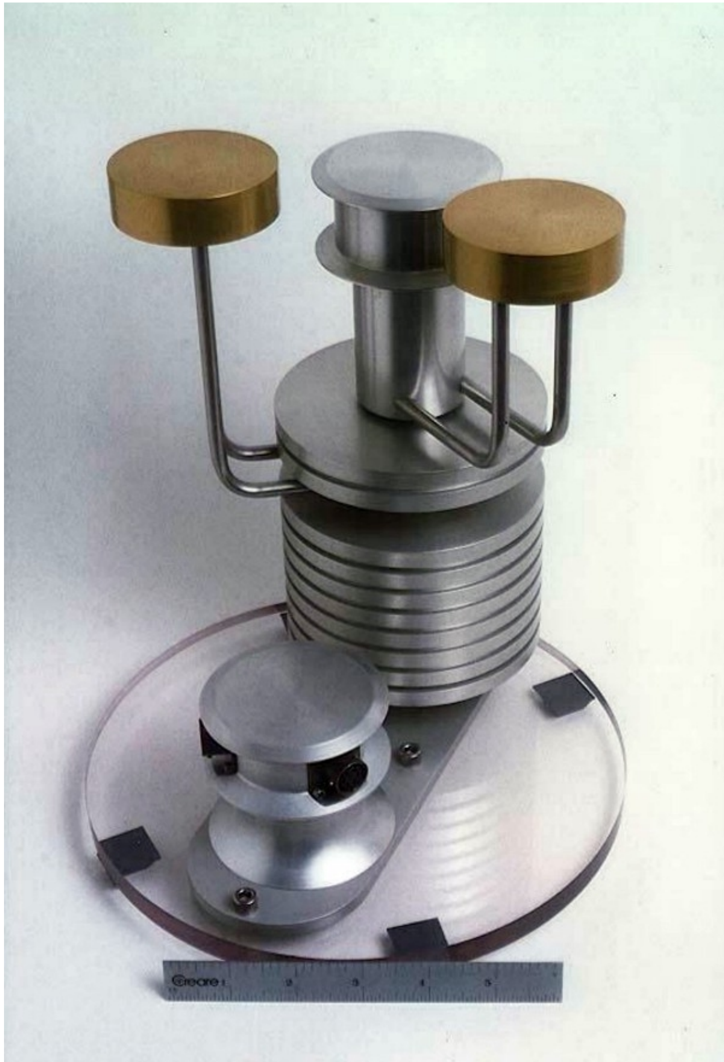
- 5 eV resolution at 6 keV (Milano)
- arrays of NTD on bond wire cantilevers (SAO)





Constellation-X Technology Roadmap
Microcalorimeter Cooling System

Develop long life, low weight, low cost, low vibration cooling systems



Microcalorimeter cooling system

Required technology

- Mechanical cooler for thermal shields and for heat sink for sub-Kelvin cooler at 4 – 8 Kelvin
- Multi-stage ADR system to reach 40 – 65 mK

Investigate alternative technologies

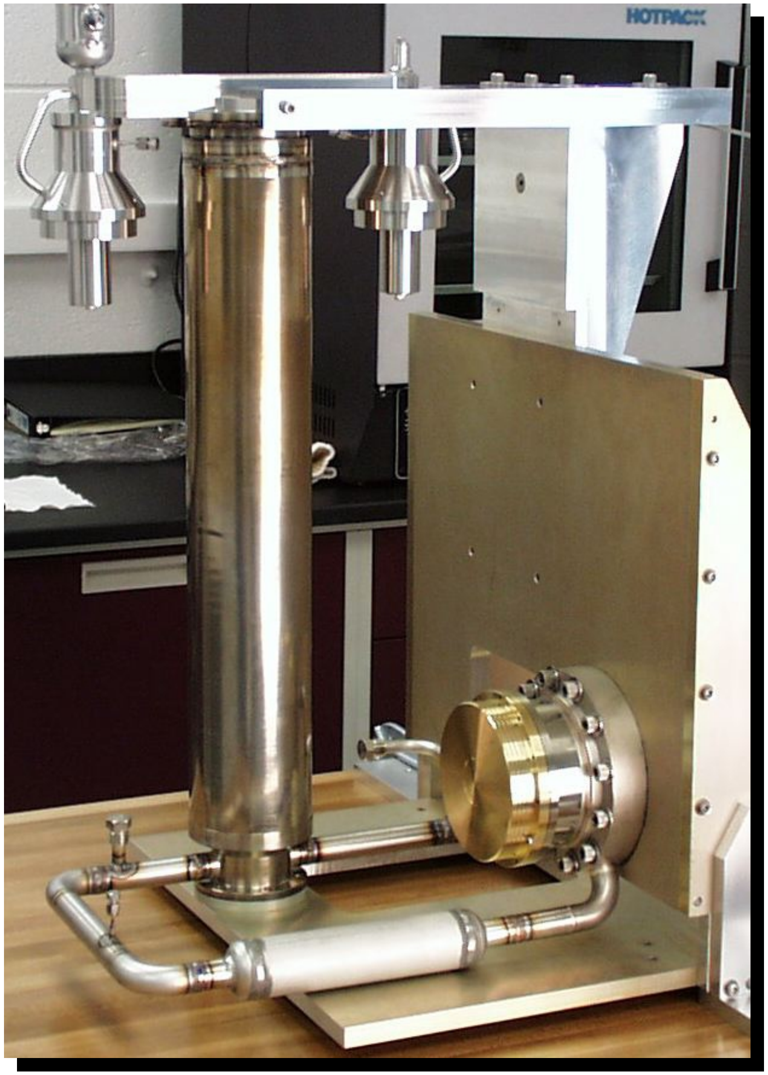
- Dilution refrigerator vs ADR
- Hybrid Stirling/J-T cooler vs Turbo-Brayton cooler

Recent progress

- 70 Kelvin turbo-Brayton cooler flown on HOST shuttle mission
  - HST Third Servicing Mission scheduled for August, 1999
- 5-50 mW @ 4-10K breadboard being fabricated for test in late 1999

Require funding for multi-stage ADR development

Progress to Date (January 1999): Coolers



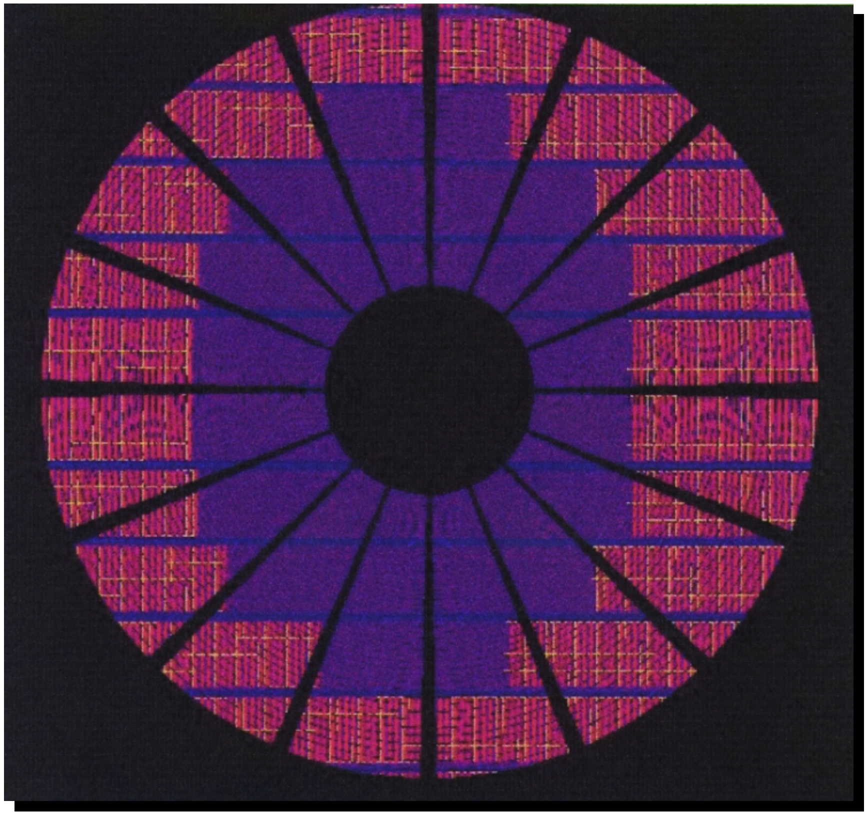
Reverse Brayton cooler

- 70 Kelvin cooler for Hubble Space Telescope (NICMOS) successfully flown on HOST shuttle mission
  - thermodynamic performance within 2% of predictions
- 5 watt, 65 Kelvin cooler completed two years of endurance testing
- Completed cold bearing test on 35 Kelvin cooler
- Compressor for NICMOS demonstrated “proof of principle” that turbo-Brayton cooler can be operated efficiently at low power
- First performance test of cold bearings at 10 Kelvin scheduled for winter, 1999

Sorption Cooler

- Engineering model 20 K sorption cooler fabricated for balloon experiment

Constellation-X Technology Roadmap
Grating/CCD Spectrometer



- The Grating/CCD spectrometer on Constellation-X will offer unprecedented sensitivity and resolution in the line-rich, low energy (E < 1 keV) X-ray band.
- Effective area more than an order of magnitude better than that of the grating spectrometers on AXAF and XMM will be achieved.
- The design builds on the successful technical heritage of XMM and AXAF.
- Important new technology developments will include
  - Significant reduction in the mass per unit area of the grating array
  - Improved diffraction efficiency and reduced scattering from the individual grating elements
  - Significant reduction in the power consumption and total mass of the CCD and their associated read-out electronics
  - Improved low energy quantum efficiency in the CCDs

Progress with Grating/CCD Technology

- A prototype grating has been fabricated using anisotropic etching of blaze-cut silicon wafers and will be tested at X-ray energies using calibration facilities at Columbia

- Resistive gate CCDs show promise for improving quantum efficiency at low energies

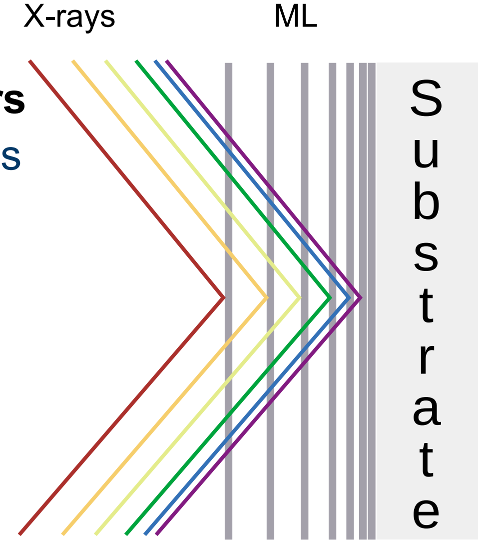
Constellation-X Technology Roadmap
Hard X-ray Telescope: Optics and Detectors

OPTICS

Primary approach - segmented shells coated with graded multilayers
- Substrates - thermally-formed glass microsheet or epoxy-replicated foils
- Multilayers - Tungsten/Silicon or Platinum/Carbon graded-spacing

Secondary approach - integral shells with graded multilayers
- Multilayers - replicated or coated onto interior of shell

Required Technical Development
- Demonstrate 1’ angular resolution for prototype optic (improve from 3’)
- Improve multilayer reflectivity - minimize interfacial roughness
- Develop multilayer replication or interior coating technique



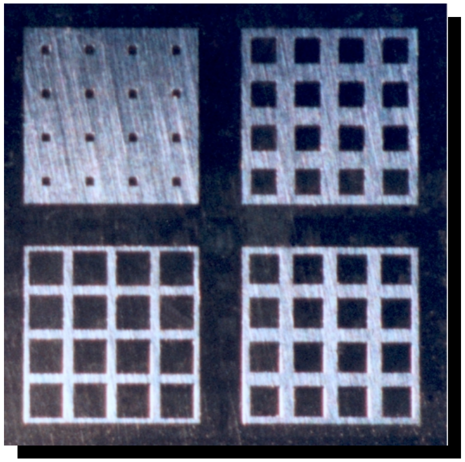
Principle of Graded Multilayer Optics

DETECTORS

Primary approach - high-Z solid state pixel detector
- Material - room temperature semiconductor (CdZnTe, CdTe)
- Readout - custom low-power, low-noise ASIC

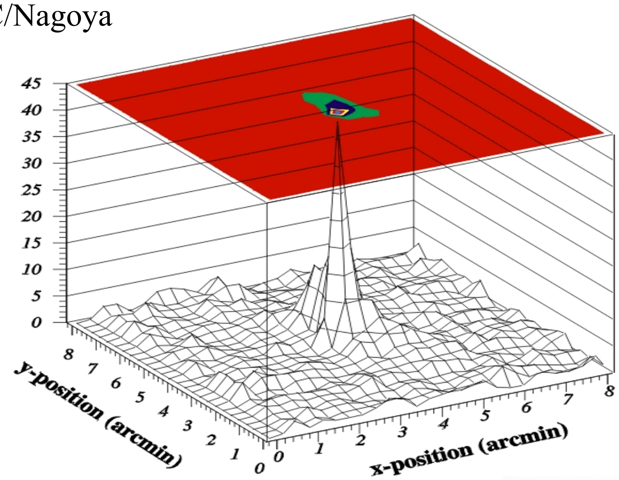
Secondary approach - Silicon strip detector
- Vertically stacked detectors to achieve high-energy response

Required Technical Development
- Demonstrate CdZnTe material uniformity in appropriate dimensions
- Develop segmented contact technology for CdTe
- Demonstrate low-noise ASIC readout



Progress to Date (January 1999): Hard X-ray Telescope Optics

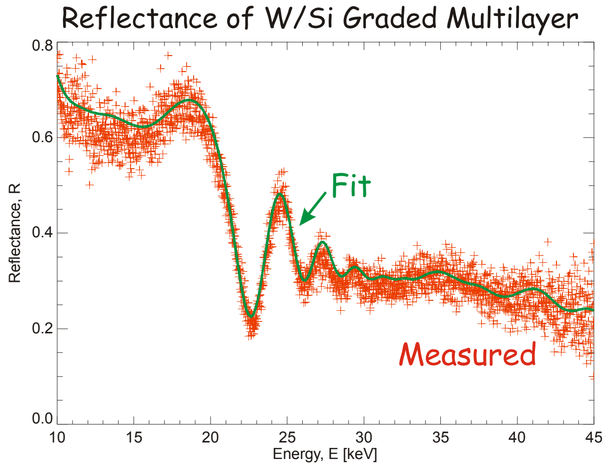
GSFC/Nagoya



- Image at 30 keV achieved in August 1997 using Pt/C multilayer on an epoxy replicated foil mirror shell by GSFC/Nagoya -- 30 layer pairs, 0.13 micron thick, $\leq$3' HPD with no distortion of foil due to stress

- 45" individual shell figure measured for coated 200 layer pair W/Si optics. Multilayer roughness - 3.5 Angstroms.

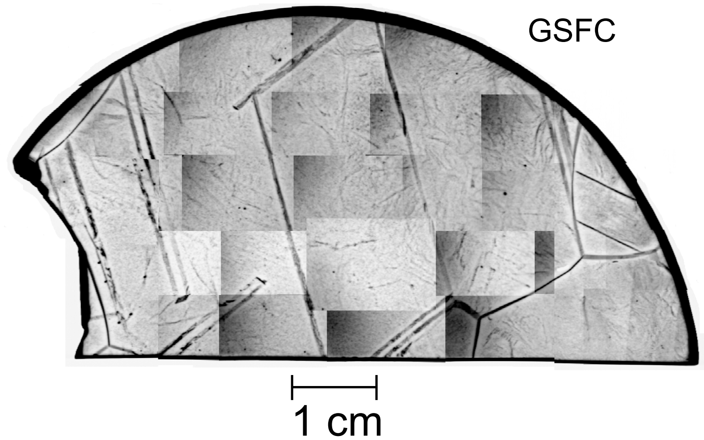
Caltech/Columbia/Lucent



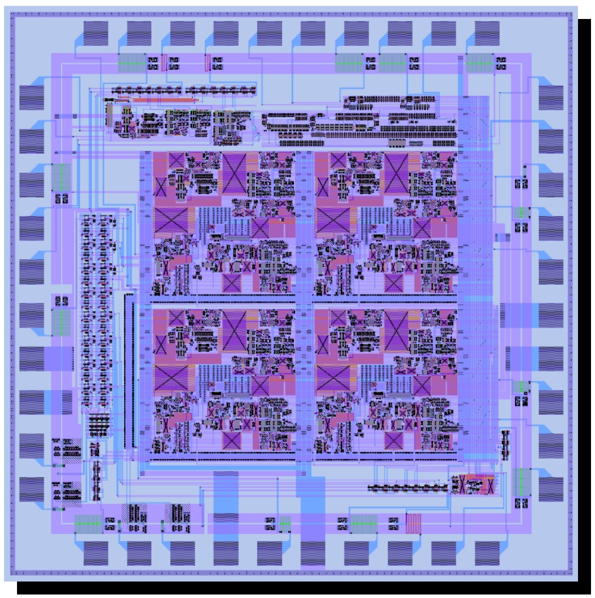
W/Si coated thermally-formed glass

Progress to Date (January 1999): Hard X-ray Telescope Detectors

- Development of IR/X-ray scanning for material selection for large (2.5 cm) devices
- Hybridization techniques developed for large devices and for tiling small devices
- Characterization of CdTe and CdZnTe pixel detectors.



IR Transmission scan of CdZnTe wafer for selection of detector material


Caltech

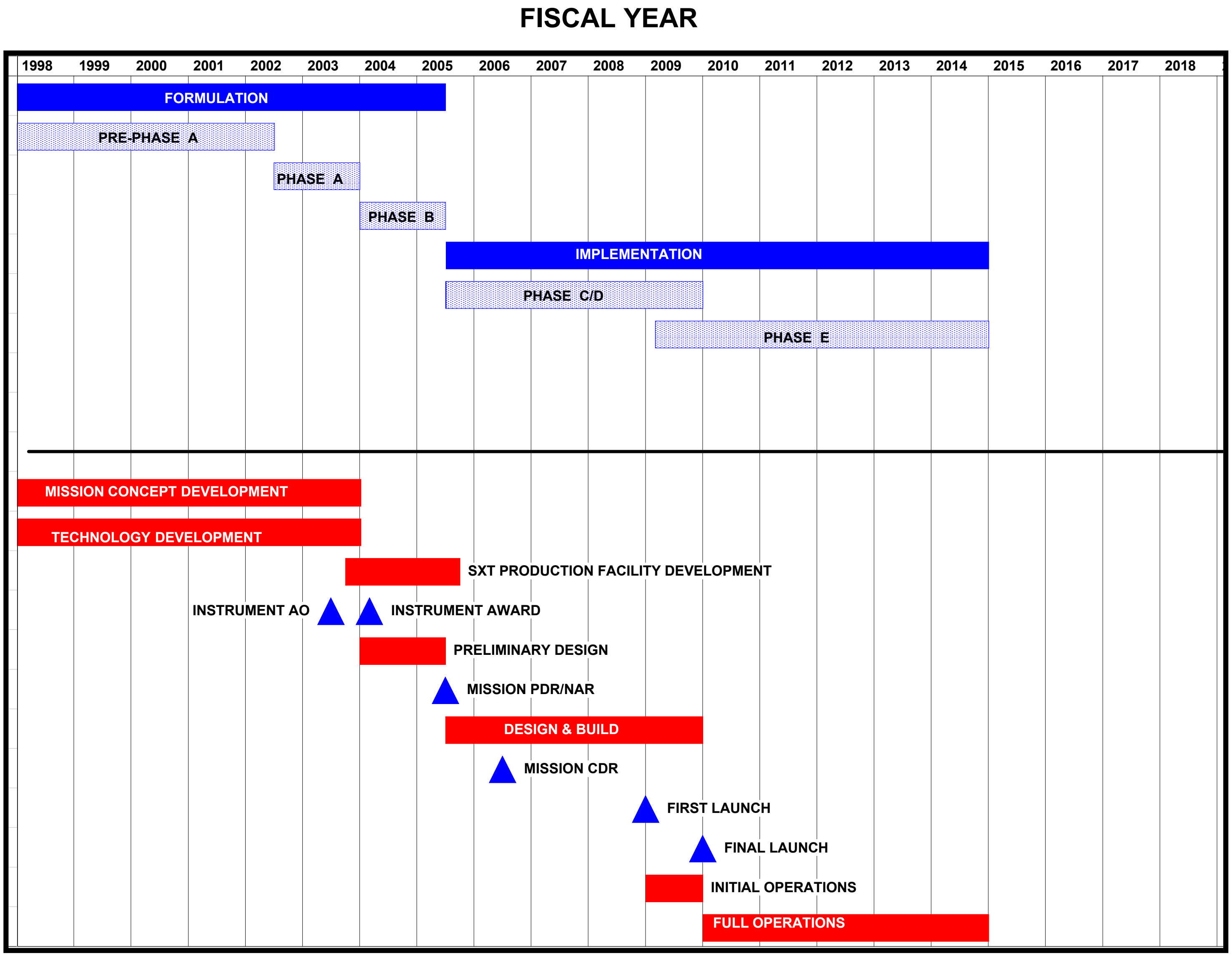
Layout of a single pixel low-noise VLSI readout.

- Prototype low-noise 500 micron pixel VLSI tested

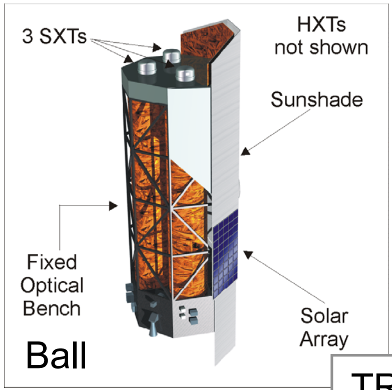
  0.25 keV equivalent electronic noise (with representative pixel capacitance

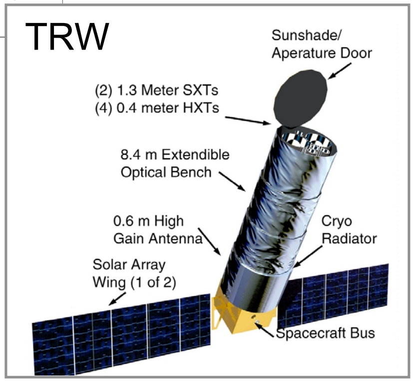
  250 υWatt/pixel

Top Level Schedule for 2005 New Start



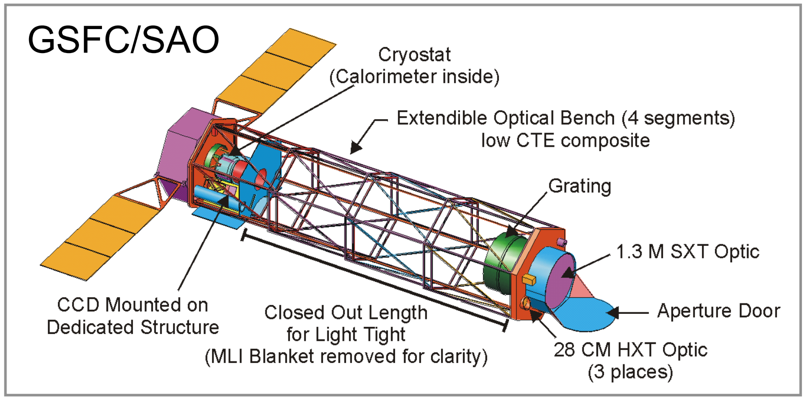
Mission Studies





CAN Studies by Ball and TRW

- May to September 1998, Ball and TRW made independent assessments of the possible mission approaches
- CAN studies with TRW and Ball validate overall approach and approximate s/c costs



In House Design by GSFC/SAO

- Baseline of a six s/c Delta II class mission

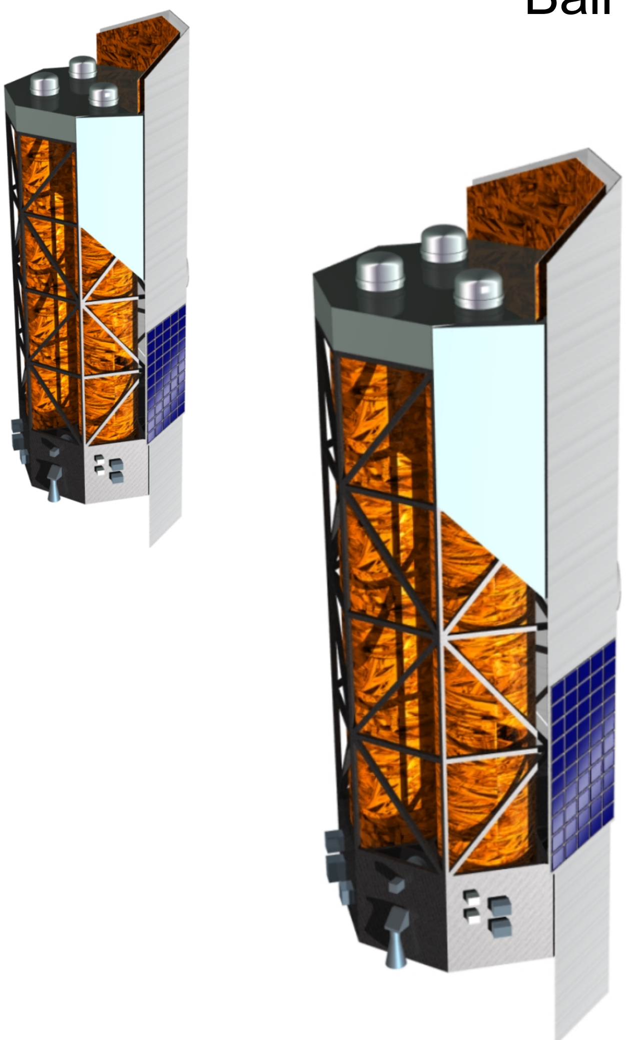
TRW Baseline Configuration

TRW examined 6, 3 and 2 s/c Constellation-X designs

- selected baseline of 3 s/c
- two 1.3m SXT plus six HXT per s/c
- Extendible optical bench
- simple s/c bus, based on existing design
- launched with optic looking up
- total observatory mass is ~3700 kg
- requires three EELV

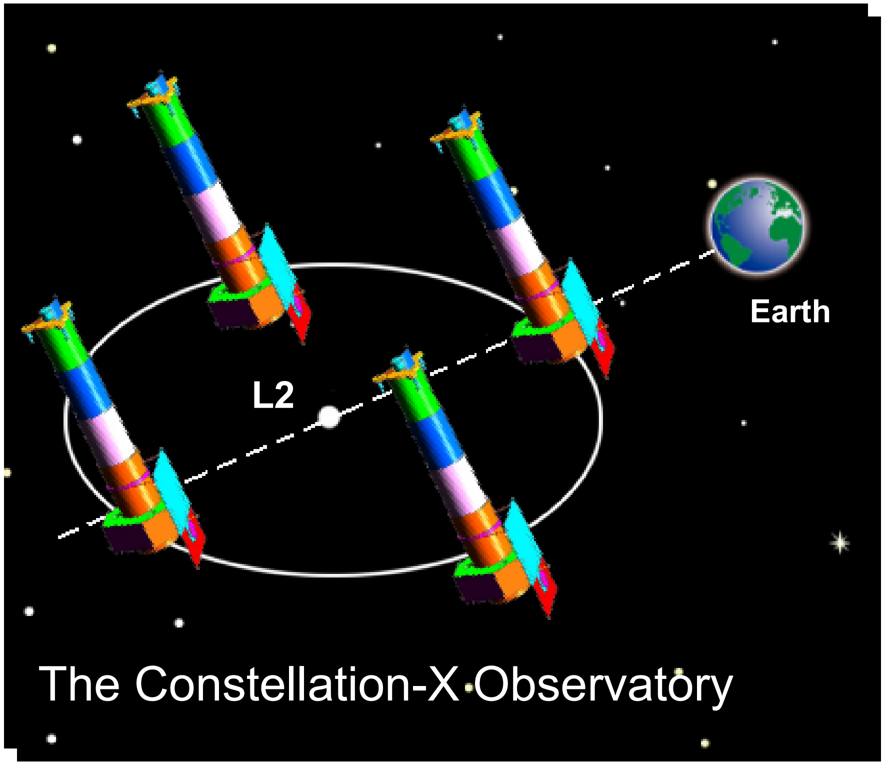
Ball Baseline Configuration

Ball examined 6 and 2 s/c designs



- selected baseline of 2 s/c
- three 1.3 m SXT plus 14 HXT per s/c
- fixed optical bench - using large Delta IV shroud
- option given to split 1 s/c into 3 smaller versions
- launched with optic looking down
- has cold and warm ends to the design
- requires two EELV

Orbit Choice

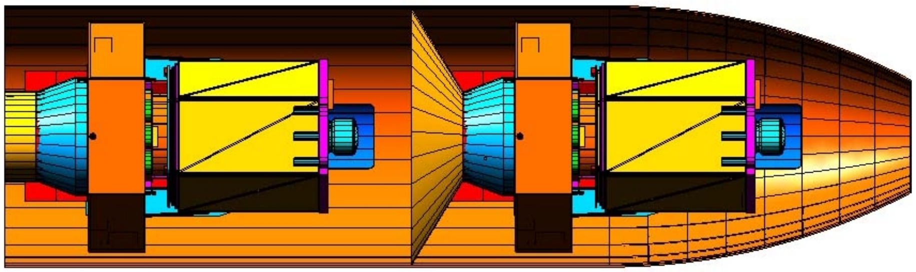


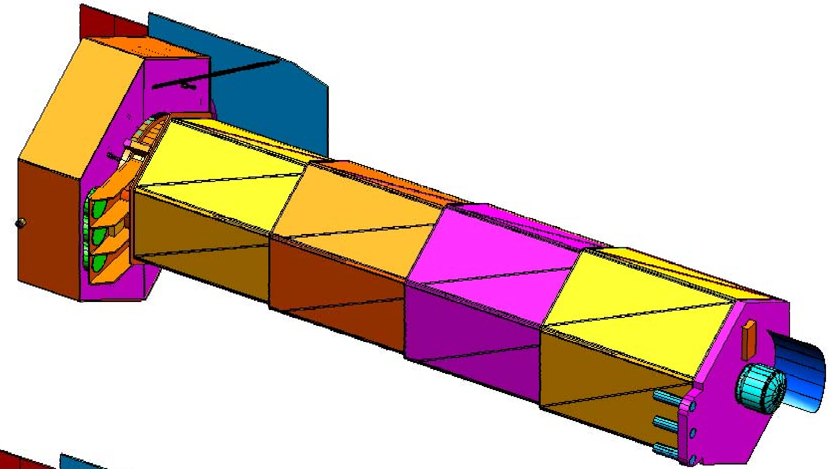
- Low earth and high earth options studied by GSFC/SAO, Ball, and TRW
- High Earth Lissajous favored in all three studies as the lowest risk and most cost effective design
    - High observing efficiency: LEO requires 2-3 times more collecting area
    - Optimum thermal environment for long-lived, low-weight cryo
    - Much simpler s/c design

Launch Costs

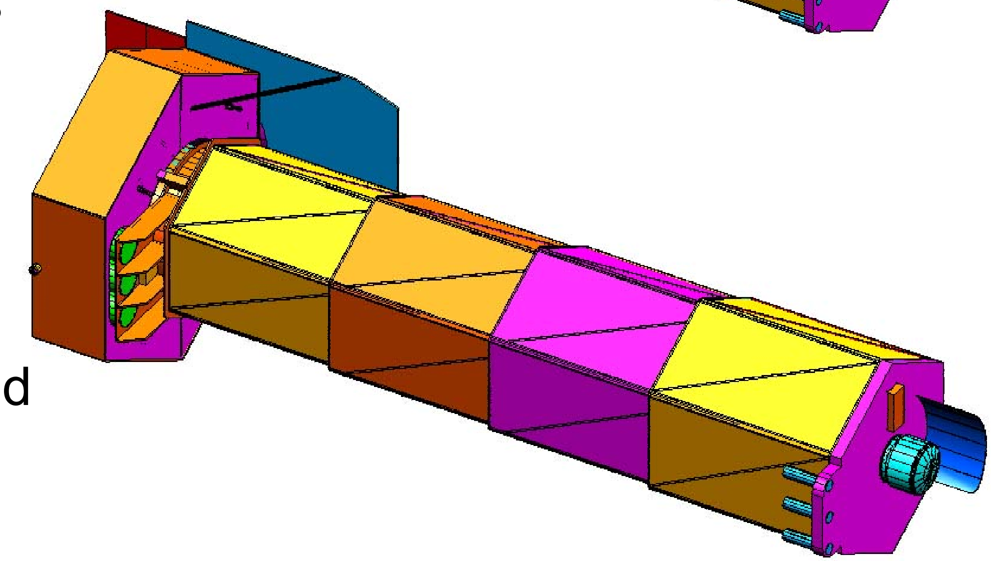
- Results of EELV procurement now available
  - EELV Medium plus launcher at expected cost
  - No Delta II class vehicle available
- "Real" launch capability which flies Constellation-X to L2 with two EELV Medium plus cost of $165-175M
  - Meets cost estimate of $180M!
- Redefined GSFC/SAO baseline to fit this new capability

Latest GSFC/SAO Baseline





- Four s/c on two EELV Medium Plus
- To preserve collecting area, increased diameter of SXT optic to 1.6 m and focal length to 10 m
- Look down design provides
  - low-mass s/c
  - optimal thermal design (cold and warm ends)



International Collaboration

International participation in the Constellation X-ray Mission is encouraged

- Too soon to make specific agreements on contributions until the technology is selected
- Current emphasis on contributing to the technology development program

Current arrangements and teaming:

- Osservatorio Astronomico di Brera (Italy)/SAO/MSFC developing lightweight replicated shell optics
- Nagoya University (Japan)/GSFC: Multilayers for HXT
- Danish Space Research Institute/CalTech: Multilayers for HXT
- MSSL (UK)/GSFC: Two-stage ADR
- Leicester University (UK)/GSFC: Microchannel plates for HXT
- Leicester/Penn State: CCDs for a possible Grating zero order camera

Extended Constellation-X Mission

- Use C-X infrastructure to continue building units beyond baseline of 4 satellites
- Provides opportunities for improved angular resolution, higher energy resolution, expanded field of view for microcalorimeter, extension of bandpass to both higher and lower energies, as well as possibilities for advanced instruments
- Each subsequent launch (2 satellites) provides 50% increase in collecting area relative to baseline mission and/or supports extended mission life at lower cost than LEO servicing
- Estimate $125M/yr, following baseline development and launches, to support one launch (2 satellites) every two years

Summary

The Constellation X-ray Mission traces the evolution of the Universe from origins to endpoints

- the production and recycling of elements
- the origin and evolution of black holes

Investment now underway to develop advanced technology to enable the mission

- assembly line production of lightweight, high performance optics, detectors, coolers, and spacecraft
- Multi-satellite concept is low-risk

Facilitates ongoing science-driven, technology-enabled extensions:

- spatial resolution,
- collecting area,
- energy bandwidth, and
- spectral resolution

http://constellation.gsfc.nasa.gov